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SUMMARY

The problems for the supersonic transport (SST) encountered in operations in a simulated present-day Air Traffic Control (ATC) system have been studied in real time by using an SST aircraft flight simulator and the Federal Aviation Administration (FAA) ATC simulation facilities. Airline crews operated the SST flight simulator, and experienced air traffic controllers operated the ATC simulation facilities. Design study configurations of the SST were used in the tests. The test program consisted of departures and arrivals under weather conditions which required operation by FAA Instrument Flight Rules in the New York, New York, and San Francisco, California, terminal areas.

The investigation showed that on established departure and arrival routes the SST was required in many instances to make substantial changes in heading at low supersonic speeds. For departures, such turns were detrimental to performance; straight-line route segments from 120 to 170 nautical miles long for SST supersonic acceleration were considered to be highly desirable. On the basis of fuel allowances provided under the Tentative Airworthiness Standards for Supersonic Transports (Nov. 1, 1965; Revision 4, Dec. 29, 1967), terminal area maneuvering in the New York area consumed on the average up to 40 percent of the en route contingency fuel in departures and up to 38.6 percent in arrivals. Operation of the SST along a climb corridor for domestic departures at John F. Kennedy International Airport, New York, was found to be feasible without violating existing restricted airspace outside the airport area. Such operations reduced the amount of time for the SST in the congested airspace below 40 000 feet (12.19 kilometers) by about one-half and resulted in savings of 1 to 2 percent of mission fuel. Crew workload associated with ATC communications and navigation was not, in general, enough higher than that for subsonic-jet-transport operations to elicit adverse comments from the pilots.

INTRODUCTION

The integration of a new aircraft with different performance characteristics into the Air Traffic Control (ATC) system has ramifications for both the aircraft and the system. Failure to plan for the introduction of a new aircraft can result in unnecessary penalties for the new aircraft in complying with ATC procedures designed for current aircraft. Similarly, the safety and traffic-moving capability of the ATC system may be jeopardized by a new aircraft for which handling procedures have not been developed.

Planning for the introduction of the forthcoming supersonic transport (SST) into the ATC system is particularly pertinent. Because the SST will cruise three times faster at twice the altitudes of current subsonic jet transports, problems in communications, flight-path control, weather-data collection and dissemination, and organization of airspace are anticipated. Large variations in performance (climb and acceleration) capability over the flight regime reflect in problems of establishing separation standards and lead times required for altitude assignments. Higher sensitivity to off-optimum operating conditions and the low ratio of payload to fuel reserves make expeditious ATC handling even more important for the SST than for current aircraft.

Recognition by both the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) of these anticipated problems with regard to the introduction of the SST into the ATC system has resulted in preliminary ATC simulation studies by the FAA (ref. 1) and an exploratory flight program by the NASA (ref. 2). In order to study these problems in more depth, the NASA and FAA have subsequently conducted a cooperative program by using the FAA ATC simulation facilities located at the National Aviation Facilities Experimental Center, Atlantic City, New Jersey, and a fixed-base SST simulator located at the NASA Langley Research Center, Hampton, Virginia. The joining of these facilities by telephone data links provided a research method by which proposed designs of the SST could be studied in simulated real-time ATC environments. Airline crews were used in the SST simulator which provided a realistic flight-compartment environment. Experienced air traffic controllers manned the ATC simulator which was programed to represent the present-day ATC system.

For the NASA, the purpose of the present program was to study such operational factors as instrumentation and fuel requirements, navigation problems, and crew workload for the SST in ATC environments. The present-day ATC system was selected for the initial environment to define the primary problems connected with the introduction of the SST and to provide a basis for the assessment of the solutions to be tried in concepts of the future ATC system. Design study configurations of the SST were used in the investigation. The FAA results on SST airspace requirements, priority effects, and ATC handling requirements in the present-day system have been reported in reference 3.

SYMBOLS

M	Mach number
Δp	sonic-boom overpressure level, pounds force per square foot (newtons per square meter)
$(T/W)_{TO}$	thrust-to-weight ratio at start of take-off
x	east-west ground coordinate, nautical miles
y	north-south ground coordinate, nautical miles
z	vertical coordinate, feet (kilometers)

ABBREVIATIONS

ARTCC	Air Route Traffic Control Center
ATC	Air Traffic Control
DME	distance-measuring equipment
FAA	Federal Aviation Administration
FL	flight level (pressure altitude in hundreds of feet)
IFR	Instrument Flight Rules
ILS	instrument landing system
JFK	John F. Kennedy International Airport
KIAS	knots indicated airspeed
LRC	Langley Research Center (NASA)
NAFEC	National Aviation Facilities Experimental Center (FAA)

PND	pictorial navigation display
SFO	San Francisco International Airport
SID	standard instrument departure
SST	supersonic transport
VHF	very high frequency
VOR	VHF omnirange radio navigation station
VORTAC	VOR station with DME provision

EQUIPMENT

A block diagram of the equipment and the interconnections of this equipment are given in figure 1. At the NASA Langley Research Center, a simulator flight compartment connected to the analog-computer facility was used to represent the SST design being investigated. This equipment was connected to the FAA ATC simulator at the National Aviation Facilities Experimental Center (NAFEC) in Atlantic City, New Jersey, by means of data and voice-communication telephone lines.

SST Simulator

General.- A plan view of the flight compartment and control room of the fixed-base aircraft flight simulator used to represent the SST is shown in figure 2. The flight compartment was similar to that of current jet-transport aircraft. The flight instrumentation used, which included a modern flight-director system, was also similar to that used in current jet-transport aircraft with instrument ranges modified to cover the higher altitude, speed, and vertical velocity ranges of the SST. Because of the lack of acceleration cues in the fixed-base simulator, a flashing red light triggered by a deviation of 0.2g or -0.2g in normal acceleration from the 1.0g unaccelerated flight condition was used on the flight instrument panel to alert the pilot to the onset of uncomfortable g-level operations. An interior view of the flight compartment is shown in figure 3.

Accessory equipment.- Accessory equipment needed to provide for navigation, communication, recording, and data transmission was located in a room behind the flight compartment (fig. 2). The radio aids equipment provided for simulation of ground-based navigation aids which included up to six VORTAC stations, marker beacons, and an instrument landing system (ILS). The communications equipment provided the switching

capability required in implementing the simulated VHF radio communications between the pilots and the air traffic controllers over the telephone lines. A dual-channel tape recorder was used to preserve conversations between pilots and air traffic controllers. Two 30- by 30-inch (76.2- by 76.2-centimeter) x-y plotters were used to record the ground track: one on a terminal area map covering an area of 120 by 120 nautical miles; the other on an en route area map covering an area 400 by 400 nautical miles.

Analog computer.- The characteristics of the SST were programed on five analog computers. (Two of these analog computers are shown in fig. 4.) Equations for six degrees of freedom were used in the representation of the aircraft motions. The motion of the simulated aircraft was controlled by signals to the computers generated by movements of the flight controls by the pilot. In return, signals from the computers operated the aircraft instrument displays which provided the pilot with information on the flight status of the aircraft. The computer program was scaled to cover a Mach number range from 0 to 4.0 and an altitude range from sea level to 100 000 feet (30.48 kilometers). The characteristics of the engines and other aircraft systems were also programed in the computer. Engine thrust and fuel flow characteristics were expressed as functions of Mach number, altitude, and throttle position for four independent engines.

Pictorial navigation display.- For some of the tests, an optical projector-type pictorial navigation display (PND) was installed in the lower center part of the flight instrumentation panel in place of the simulated weather radar display. The pictorial navigation display is shown in figure 5. For illustrative purposes, a terminal area map is positioned over the $5\frac{1}{2}$- by $7\frac{1}{2}$-inch (14- by 19-centimeter) screen to represent the projected view as seen by the pilot. Features of the display include a north-oriented moving map with an aircraft symbol fixed in position in the center of the screen. The aircraft symbol and attached cursor rotate with change in heading. A heading scale is provided at the edge of the screen. A control panel allowed a selection of either en route or terminal area maps. The en route area map had a scale of 10 nautical miles per inch (3.94 nautical miles per centimeter); the terminal area map had a scale of 5 nautical miles per inch (1.97 nautical miles per centimeter). The maps depicted only basic airway, navigation, and ATC information. A more complete description of this equipment is included in reference 4.

Course-line computer.- The basic radio aids equipment was modified for some of the tests by the addition of computing equipment to provide course-line computer capability. This capability allowed the pilot to relocate effectively the tuned VORTAC station by 5 or 10 nautical miles to either the right or left of the airway course to the station (phantom station concept). Selection by the pilot of the airway course on the radio magnetic indicator with the course-line computer set to relocate the tuned station provided the inputs to the flight-director element of the attitude-director indicator for navigation along a track displaced and parallel to the airway.

ATC Simulator

The real-time simulated ATC environment was created by means of a combination of an ATC facilities simulation and an air-traffic sample simulation. Both of these simulations were provided by the FAA and created the environment in which the SST simulator was operated for the tests.

The ATC facilities simulation consisted of entire and partial Air Route Traffic Control Centers (ARTCC) as required and an Approach Control and Tower complex for one airport. The area controlled was 400 by 400 nautical miles. Figure 6 shows part of an ATC facility simulator typical of those used in the tests. The ATC facilities were staffed by approximately 30 experienced air traffic controllers. The controllers were provided with modern television-type brightly lit radar displays with video maps showing airways, holding and terminal areas, and navigation aids, as well as the usual flight progress strips and interphone and radio communications equipment.

The air-traffic sample simulation was created by as many as 108 electronic target generators. A photograph of some of the radar target generators is shown in figure 7. Each target generator was programed to have the generalized characteristics of a particular type of aircraft. Propeller-driven, subsonic jet, and SST aircraft were programed in the proper numbers to create the desired traffic sample. The operator of each target generator navigated the aircraft by maneuvering a spot of light along the airways map at the top of the console and flew the aircraft on climb and descent profiles by means of a control panel. The flight was conducted according to a programed script and instructions from the air traffic controllers received over a simulated radio communications network. The x,y position data (ground coordinates) from the target generator were fed through radar simulators which transformed the data into radar form; that is, properly gated, target video pulses and antenna position. The video pulse and antenna position data were fed to the controller displays to provide the air-traffic sample.

Data Transmission and Communications

Data transmission between the SST simulator and the ATC simulation facilities was effected over leased private telephone lines. A block diagram of the data transmission system is shown in figure 8. The SST simulator ground coordinates x,y and altitude z information were transmitted over a data phone line to the ATC simulation facilities. A digital radar beacon transponder signal was also transmitted from the SST simulator over this system. The SST simulator position information joined the position information from the target generators in the simulated radar system for display on the controller radar displays and for recording in the data collection system. The beacon transponder information from the SST simulator (reinforced radar signal and beacon code set in by

the pilot) joined the beacon transponder information from the target generators in the simulated radar beacon system for display on the controller radar displays.

Communications between the radar target-generator operators and the air traffic controllers was effected by a special telephone switching system. This extremely versatile telephone system allowed many target-generator operators to dial the same controller simultaneously and, thus, actual radio communications were simulated. Communication between the pilots of the SST simulator and the controllers was effected over two long-distance lines which were connected into the special telephone system. Selection of an assigned frequency on the VHF radio-communications control panel in the SST cockpit automatically dialed the line in the special telephone system to the controller with whom communications were desired.

TEST PROGRAM

General

The test program was designed to study in separate phases arrival and departure operations under IFR conditions into and out of JFK in the New York ARTCC area and SFO in the Oakland ARTCC area. The test environments for domestic and oceanic operations in the New York area and for domestic operations in the Oakland area were 400 by 400 nautical miles. The test environments and airway system used are shown in figure 9. The New York environments included parts of the New York, Boston, and Cleveland Air Route Traffic Control Centers, the New York Oceanic Control Sectors, and the JFK Approach Control and Tower complex. The Oakland environment included parts of the Oakland, Seattle, and Salt Lake City Air Route Traffic Control Centers and the SFO and Oakland Approach Control and Tower complexes.

The traffic samples used included current-type reciprocating-engine, turboprop, civil and military subsonic jet, and SST aircraft. The supersonic transports represented included the Anglo-French Concorde (cruise Mach number of 2.2) as well as U.S. design study configurations (cruise Mach number of 3.0). Situations were developed of moderate traffic density in the New York area and of heavy traffic density in the Oakland area relative to current traffic-density levels in each locality.

All traffic was under the positive control of an ARTCC or airport departure, arrival, and tower facilities. The following assumptions were made: (1) radar and radio communications coverage existed throughout the area, (2) navigational facilities were suitable for navigation at all altitudes, and (3) ceiling and visibility conditions at the destination airport were equal to the minimum values allowable for landing.

SST Characteristics

Two SST design study configurations were used, both having a cruise Mach number of 3.0. Configuration A had a wing with variable sweep and turbojet engines; configuration B had a fixed-delta wing and turbofan engines. The turbojet engines were equipped with afterburners and the turbofan engines with duct burners for thrust augmentation. Both configurations had the same take-off thrust-to-weight characteristics. (See table I.) Configuration A had a transonic acceleration capability somewhat higher than configuration B because the engines were sized for cruising without afterburning rather than sized to meet the transonic acceleration requirement. The wing design with variable sweep had nearly twice as much wing loading at maximum gross weight as the delta-wing design. Configuration A was used in the New York oceanic operations; configuration B was used in all other operations.

TABLE I.- SST CHARACTERISTICS

Characteristic	Configuration	
	A	B
Maximum $(T/W)_{TO}$, unaugmented	0.32	0.32
Minimum transonic acceleration, ft/sec^2 (m/sec^2)	1.6 (0.49)	1.4 (0.43)
Wing loading, lbf/ft^2 (kN/m^2)	107 (5.12)	56 (2.68)

For both configurations, the basic aircraft damping was augmented about all three axes to provide satisfactory handling qualities.

SST Operating Procedures

The SST simulator was operated by teams each consisting of a captain and first officer. The crews from Trans World Airlines and United Air Lines included pilots in airline supervisory and management positions as well as those engaged in full-time scheduled airline operations. Airline experience of crew members varied from 8 years (4000 flight hours) to 28 years (22 000 flight hours).

A typical departure operation for the SST simulator was initiated just prior to scheduled departure time by a radio call from the crew to ATC departure control for clearance instructions and ended when cruise conditions were established. Arrival operations were initiated in cruising flight by a radio call from the crew giving an estimated time of arrival over a prescribed location and ended at touchdown on the runway.

The climb and descent schedules used and the engine, structural, and sonic-boom profile-limitation boundaries for configurations A and B are illustrated in figure 10.

For both configurations, maximum unaugmented thrust was used for take-off and initial climb. After take-off, thrust was reduced, however, to hold the airspeed between 200 and 250 KIAS during the large heading changes and during the step-climb operations required in terminal area maneuvering. During the climb, full augmented thrust was applied at about 20 000 feet (6.10 kilometers) for configuration A and at about 31 000 feet (9.45 kilometers) for configuration B and continued until it was reduced at approach to cruise conditions. For both configurations, the climb consisted of a constant indicated-airspeed segment, a Mach number – altitude schedule which represented a sonic-boom overpressure limit of 2.0 pounds force per square foot (95.76 newtons per square meter) and a final constant indicated-airspeed segment to initial cruise conditions.

The descent for both configurations was performed by using flight-idle thrust. The descent profiles in both cases consisted of a slowup at cruise altitude followed, in general, by constant airspeed or constant Mach number segments. For configuration A, a level flight slowup to a Mach number of 0.9 was necessary, however, at 50 000 feet (15.24 kilometers) to keep the sonic-boom-overpressure level below 1.5 pounds force per square foot (71.82 newtons per square meter). Reduction in speed to 250 KIAS was made on approach to the terminal area and to lower airspeeds as requested by the ATC approach controller. Deceleration in the descent was increased, as needed, by the intermittent use of speed brakes. For passenger comfort a limitation of 0.2g (19.63 meters per second^2) in longitudinal deceleration was imposed in the use of speed brakes. In some cases, in-flight thrust reversal was used to steepen the descent so as to arrive over a prescribed location at the altitude specified by the controller. For the domestic arrivals at SFO, the descent schedule of configuration B was modified to a single constant-airspeed segment of 300 KIAS so as to simplify the programing of the descent-schedule command guidance on the flight-director indicator.

Manual inputs were used for the control of both horizontal and vertical flight paths with horizontal and vertical navigation guidance provided by the flight-director system. For vertical guidance along the sonic-boom-overpressure limit boundary, the flight-director element of the attitude-director indicator, which was programed to display the pitch-trim input required to return to the Mach number – altitude schedule, was employed. For configuration A, the wing sweep angle was automatically increased and decreased with Mach number as shown in figure 11. The lag of 0.2 in Mach number between the increasing and decreasing sweep-angle schedules was provided to prevent oscillations in wing sweep angle induced by speed variations associated with the phugoid motion.

ATC Procedures

In general, present-day ATC procedures for control of air traffic (ref. 5) were used with no preferential treatment for SST aircraft. Airspace was sectored geographically and by altitude for ARTCC and airport departure, arrival, and control tower functions in accordance with present practice at the facility represented. Established standard instrument departure (SID) and terminal arrival routes were used (fig. 12). All aircraft were subject to step-climb and step-descent limitations associated with SID altitude restrictions and handoff (controller-to-controller transfer) procedures. For arrivals, a speed limit of 250 KIAS was prescribed for the zone within a radius of 30 nautical miles of the airport. Speed changes were requested by the controllers as required to effect aircraft spacing for safety purposes and for expediting the flow of traffic. Radar vectoring was used by the controllers to shorten SID and arrival routes when traffic conditions permitted. Standard subsonic jet holding procedures were used for the SST. The preferred holding altitudes for minimum fuel consumption at the holding speed of 250 KIAS were 13 000 to 25 000 feet (3.96 to 7.62 kilometers). Present-day minimum separation standards of 3 to 5 nautical miles horizontally or 1000 feet (0.30 kilometer) vertically below 29 000 feet (8.84 kilometers), 3 to 5 nautical miles horizontally or 2000 feet (0.61 kilometer) vertically between 29 000 and 55 000 feet (8.84 and 16.76 kilometers), and 10 nautical miles horizontally or 5000 feet (1.52 kilometers) vertically above 55 000 feet (16.76 kilometers) were used.

For some tests, pictorial navigation display (PND) routes were used in the terminal and en route areas. The PND routes are shown by dashed lines labeled as E6, CYN1, TA3, ED1, and so forth, in figure 13. These routes were designed with some independence from the normal routes. Arrival flight routes were independent to a point within the approach control area where they were combined with the normal vector routes of subsonic aircraft. The PND departure routes were separated from and parallel to current SID routes to a point in the ARTCC area where SST aircraft were normally above subsonic traffic. For these tests, SST aircraft were not radar vectored by the controllers but were navigated by the crew along the assigned routes. The pictorial navigation display was used for navigation along the curved segments of the PND routes and used with a course-line computer for navigation along the straight segments of the PND routes.

Most departure operations from JFK were made from runway 31L followed by a tight left turn to one of the SID routes shown in figure 12(a). This tight left turn was required to avoid penetrating airspace allocated to La Guardia Airport landing operations. Altitude restrictions of 2500 feet (0.76 kilometer) and 4000 feet (1.22 kilometers) as shown in figure 12(a) were observed as required by traffic conditions. Oceanic departures were made along the Hampton 5 SID Route to the V139 airway, by following either route J62 or V46 (fig. 9(b)) to Nantucket (ACK) with a transition to either

COD or South Bangor (SBG). Oceanic arrival operations were initiated at either point "C" or point "D" (fig. 9(b)) and proceeded through Nantucket (ACK), Hampton (HTO), Riverhead (RVH), to Deer Park (DPK) where the terminal arrival route shown in figure 12(b) was followed. Arrival traffic was restricted to 6000 feet (1.83 kilometers) on the route segment from Deer Park (DPK) until it had passed the crossing departure traffic from JFK.

Domestic departure operations from JFK followed either the Huguenot 4 SID route or the Dutch 6 SID route (fig. 12(a)). Huguenot 4 departures followed route J70 to Erie (ERI) as shown in figure 9(a). Dutch 6 departures followed either route J80, route J79, or route J37 at Coyle (CYN) for departures to Los Angeles, Miami, and Mexico City, respectively. Domestic departures were also made along direct routings from Coyle (CYN) to Philipsburg (PSB) to Erie (ERI) to route J70. (See fig. 9(a).) Domestic arrival operations to JFK were initiated on route J60 (figs. 9(a) and 12(b)), proceeded to Philipsburg (PSB), then proceeded either via Allentown (ABE) and Solberg (SBJ) or Yardley (ARD) to Colts Neck (COL). Most landings for both oceanic and domestic operations into JFK were made on runway 4R.

All domestic departure operations from SFO were made from runway 01R to one of the SID routes shown in figure 12(c). Departures were made via Stadium 1 and routes V199 and J88 through Ukiah (UKI) to Medford (MFR); via Richmond 3 and routes V87 and J7 through Red Bluff (RBL) to Allen (AL); and via Orinda 4 and Linden and also via Altamont 2, and Stockton (SCK) through Coaldale (OAL) and via route J58 to Wilson Creek (WC). (See figs. 9(c) and 12(c).) Some special departures via Stadium 1 with a turnback eastward at Stinson Beach to Stockton (SCK) to Coaldale (OAL) and Wilson Creek (WC) were made to simulate operating conditions under which a volume of airspace restricted to military operations (military block) required the SST to be at 60 000 feet (18.29 kilometers) before passing Duckwall. Arrival operations to SFO airport were initiated at Medford (MFR), Allen (AL), and Wilson Creek (WC) (fig. 9(c)) and used the terminal arrival routes shown in figure 12(d). The arrivals from Medford (MFR) and Allen (AL) proceeded via routes J1 and J7, respectively, to Red Bluff (RBL) and via route V87 to Napa (APC). The arrivals from Wilson Creek (WC) were via routes J58 and V244 to Stockton (SCK). All landings at SFO airport were made on runway 28R.

RESULTS AND DISCUSSION

Departures and Arrivals

Examples of departure and arrival ground tracks for both oceanic and domestic operations at New York and for domestic operations at San Francisco are given in figure 14. Mach number values are shown at intervals along the tracks. For the configurations tested, the SST attains supersonic speed within 50 nautical miles in departures

and is slowed to subsonic speeds about 100 nautical miles from the airport in arrivals. Because the SST is at altitudes above those used by subsonic transports when at supersonic speeds, the area in which the supersonic and subsonic transports are operating in the same airspace is thus contained within about a 100-nautical-mile radius of the airport. Figure 14 also shows that climbout operations were generally completed within about 300 nautical miles and descent operations (including slowup at cruise altitude) generally took about 250 nautical miles.

Corresponding examples of altitude, fuel, time, and distance relationships for the departure and arrival operations shown in figure 14 are given in figure 15. East-west distance was used in presenting the results in figure 15 to approximate the great circle distance covered in transatlantic and transcontinental missions. The fuel results are presented in terms of mission fuel, defined in the appendix. For the example shown, the fuel used in the departures varied from about 30 to 40 percent of mission fuel and the time varied from about 22 to 34 minutes. The fuel used in the arrivals varied from about 3 to 7 percent of mission fuel and the time varied from about 28 to 33 minutes. These variations in fuel and time represent the overall effects of differences in SST configurations, effects of variations in ATC procedures, such as, altitude restrictions and routing, and to some degree, pilot deviations from standard speed and thrust schedules. The sensitivity of the SST to some of these variations can be seen by a study of the results given in figure 15. For example, during New York departures, the effects of altitude restrictions for flight under arrival traffic on fuel and time are evident at altitudes below 5000 feet (1.52 kilometers) in the altitude-fuel and altitude-time plots shown in figures 15(a) and (15d). The penalties on fuel and time of the circuitous routings for New York domestic departures via both Huguenot and Dutch SID routes are apparent in the fuel-distance and time-distance plots of figures 15(c) and 15(d). Effects of substantial amounts of low-level operations and circuitous routing for New York arrivals are evident in the plots in figures 15(b) and 15(e). These apparent penalties in fuel and time indicated for deviations in a part of the mission, however, may be reduced when considered on an overall mission basis. For example, the fuel and time penalties of low-level altitude and speed-restricted operations in departures are partly compensated for by the improved transonic acceleration characteristics which result from the decreased aircraft weight.

Navigation Problems

The main navigation problem experienced in the simulated operations of the SST in the present-day ATC system was the need to make changes in course at supersonic speeds in following the established departure and arrival procedures and routes. Turns at supersonic speeds were found to be highly undesirable because of their effect on climbout performance and because they created piloting problems. For example, in New York oceanic departure operations (fig. 14(a)), the use of a bank angle of 25° (normal practice)

in the turns required at just above sonic speed, reduced the climb and acceleration capacity to zero. The result was an increase in time and fuel consumption at transonic speeds. (Fuel consumption rates are highest for the SST at transonic speeds.) Although the use of bank angles of 10° to 15° reduced the drag due to turning, fuel consumption was still high because the time required to turn was $1\frac{1}{2}$ to $2\frac{1}{2}$ times greater than the time required at a bank angle of 25°. Turns at supersonic speeds are also undesirable because the sonic-boom overpressure value may be amplified because of convergence at the ground of the shock waves generated at various times in the turn. In tests with fighter aircraft (ref. 6), pressure-buildup factors of from 2 to 4 have been recorded.

The task for the pilot in changing course at a station was found to be more difficult at supersonic speeds than at subsonic speeds because of the increased radius of turn and the increased time required to complete the heading change at the increased speed. (For a given bank angle, the radius of turn increases as the square of the velocity, and the turning rate increases inversely as the first power of the velocity.) As shown in figure 16, the radius of turn for an SST operating at a Mach number of 2 is more than 5 times greater than for a subsonic jet transport at cruise conditions; and for an SST at cruise condition (Mach number of 3), is about 12 times greater. The time required to make a heading change at a Mach number of 3 (as shown in the example for a heading change of 45° in fig. 17) is more than $3\frac{1}{2}$ times greater than the time required for a subsonic jet transport at cruise speed. Both of these factors increased the difficulty of making precise changes in course at supersonic speeds. Because of the large turn radii at supersonic speeds, the pilots tended to overshoot the outbound course considerably, as shown by the track designated nonlead turn in figure 18. Such an overshoot of the course was undesirable because interference with other SST traffic proceeding in the opposite direction was generated; thus, a need for a greater separation of traffic at such an intersection was created.

In order to avoid such overshoots, the pilots were given lead-distance information which enabled them to initiate the supersonic turn at a given slant-range lead distance (DME) before the station (fig. 19). The lead information made possible a tangential transition from the inbound course to the outbound course as shown by the track designated lead turn in figure 18. The lead distance required is a function of the heading change required, speed, bank angle, and in terms of slant-range distance, the aircraft altitude. (See ref. 7.) By use of the lead-turn information, deviations from course were reduced, and the pilot's task was eased.

Changes in course at just above sonic speed were also required in New York domestic departure operations for both Huguenot 4 and Dutch 6 SID routes (figs. 14(c) and 14(d)). In order to study the effects of providing a straight course for transonic acceleration, the Huguenot 4 and Dutch 6 SID routes were modified to incorporate radar-vectored headings prior to Huguenot and Coyle, respectively, in line with the departure routes scheduled beyond these points. (For example, see run 1, fig. 14(c) and run 2,

fig. 14(d).) The SST climb schedule was also modified in that the thrust was reduced to hold subsonic speed and FL 310 (pressure altitude of 31 000 feet (9.45 kilometers)) until the final turn onto the straight course was completed. This procedure eliminated the changes in heading at supersonic speeds and the loss in climb and acceleration capability. Such a procedure would also eliminate sonic-boom pressure buildup associated with turning.

For standard San Francisco departure operations (fig. 12(c)), the changes in course required at low supersonic speeds were, in general, smaller than for New York operations and were not as serious an operating problem. Even for the military-block departures (run 3, fig. 14(f)), the large change in course required could be completed before low supersonic speed was reached. The only substantial change in course occurred on the departures to Allen at Red Bluff. Climb and acceleration performance for this turn was not seriously affected because the Mach number was high enough to provide the increase in thrust due to ram effect. Sonic-boom pressure buildup could be a problem for such a turn, however.

Changes in course during arrival operations had no effect on performance because no turns were required until after thrust was reduced to the flight-idle condition for slowup and descent (figs. 14(b), 14(e), and 14(g)). Piloting problems related to the required heading changes at supersonic speeds were minor as long as lead-type turns were employed.

The experience gained in arrival operations indicated that provision of straight-line route segments for supersonic acceleration that begin as close as possible to the airport would be advantageous to the SST in departure operations. These straight-line route segments should be as long as the distance covered by the SST between sonic speed and a Mach number of about 2.0. For the SST configurations tested, these distances were found to vary from 120 to 170 nautical miles in length because of conditions such as aircraft weight at the beginning of transonic acceleration. Above-standard temperature conditions would increase the length of the distances required.

Climbing and descending turns.- The requirements for take-off and landing into the prevailing wind, buffer airspace between adjoining airports, community noise avoidance, ground-navigation-station siting, radar vectoring around other traffic and obstacles, and so forth, create the need for many and large changes in heading in both departure and arrival operations in the present-day ATC system. (See fig. 12.) Because most of these changes in heading occur in the terminal area, considerable time is spent in climbing and descending turns. Operations in climbing and descending turns, especially at low altitudes, are undesirable in adding to the workload of the crew in flying and navigating the aircraft, and in increasing the exposure to midair collision because of the reduction in

forward visibility for the crew and the increased difficulty of flight-path projection for the air traffic controller.

As an indication of the extent of this problem for operations of the SST in the present-day system in both the New York and San Francisco areas, the amount of time spent in climbing and descending turns is given in figures 20 and 21, respectively. Results are presented for operations on both standard and PND routes. For departures, except for domestic operations to the east from San Francisco, the amount of time spent in climbing turns averaged between 5 and 8 minutes, depending on the route, with the higher values occurring for New York domestic operations. The nearly straight-route domestic departures to the east from San Francisco averaged only about $2\frac{1}{2}$ minutes of climbing-turn operations. The somewhat higher values of time spent in climbing turns for military-block domestic operations, as contrasted to other SFO operations, were associated with the approximately 180° turn to the east required after flying a distance to the west after take-off. Flying to the west was required to attain sufficient altitude to overfly the blocked airspace. (See run 3, fig. 14(f).) Further analysis of these results indicated that from 60 to over 90 percent of the time spent in climbing turns occurred in the congested airspace below FL 400, with the higher amount occurring for the JFK domestic operations.

For the arrivals (fig. 21), the amount of time spent in descending turns averaged between $4\frac{1}{2}$ and 7 minutes, depending on the route. The highest value of 7 minutes occurred for the oceanic operations at New York. This high value reflects the considerable amount of heading change required on the oceanic arrival route to JFK. (See run 1, fig. 14(b).) Further analysis of the results for arrivals indicated that from 64 to 86 percent of the time spent in descending turns occurred below FL 200, with the higher amount occurring for the New York domestic operations.

Climb-corridor operations.- For some domestic departures from New York, climb-corridor operations were simulated by take-off, an immediate turn to a direct course towards destination, and an unrestricted climb. Figure 22 shows ground tracks for such operations for take-offs in a westerly direction (runway 31L) and an easterly direction (runway 13R). Also shown in figure 22 are the main airspace obstacles to such climb-corridor operations; that is, holding patterns, ILS courses, and airways. Flight-path restrictions associated with overflying congested areas were not considered in the operations. Noise-abatement procedures, however, were used on some of the departures from runway 31L.

The vertical (altitude and east-west distance) profiles corresponding to the ground tracks shown in figure 22 are given in figure 23 together with the pertinent airspace obstacles. These profiles are for SST configuration B. The results shown in figure 22

indicate that, in general, such a high-performance aircraft in climb-corridor operations can satisfactorily overfly the airspace obstacles outside the airport area in domestic operations from JFK.

The advantages at New York of climb-corridor operations compared with SID and PND routes are given in figure 24. The average time, fuel, and distance covered in climbing to FL 400 are shown in figure 24 for both domestic SID and PND routes (figs. 12(a) and 13(a)) and for domestic climb-corridor operations. Results for the SID and PND routes are for a thrust schedule consisting of minimum augmented thrust for take-off, thrust reduction to hold 200 to 250 KIAS in turns after take-off and for 2500-foot (0.76-kilometer) and 4000-foot (1.22-kilometer) altitude restrictions, minimum augmented thrust for climb to FL 310, and maximum augmented thrust for climb from FL 310 to cruise conditions. Three thrust schedules were investigated for the climb-corridor operations: A, the same schedule as used for the SID and PND operations (thrust reduction for 2500-foot (0.76-kilometer) and 4000-foot (1.22-kilometer) altitude restrictions and for the slight turn from runway 31L were not required, however); B, a schedule consisting of maximum augmented thrust for take-off, thrust reduction to minimum augmented thrust between 3000 feet (0.91 kilometer) and 5000 feet (1.53 kilometers) for noise abatement, and maximum augmented thrust for climb from 5000 feet (1.53 kilometers) to cruise conditions; and C, a schedule consisting of maximum augmented thrust for take-off and climb to cruise conditions. Maximum airspeed for all climbs was limited to 325 KIAS in accordance with the climb schedule shown in figure 10(b).

The results shown in figure 24 indicate that the average time spent in climbing to FL 400 can be decreased from about 10 minutes on SID and PND routes to 5 or 6 minutes by use of climb-corridor operations. Such a saving in time is advantageous to both the air traffic controller in getting the SST out of the congested airspace and to the aircraft operator in fuel and time. Furthermore, climb-corridor operations with thrust schedule A used 1 to 2 percent less mission fuel than SID and PND route operations. (Mission fuel is defined in the appendix.) The increased distance of 30 to 40 nautical miles toward destination at FL 400 for climb-corridor operations increases this advantage. Use of thrust schedules B and C, which employ maximum augmented thrust in take-off and at low altitudes instead of the minimum augmented thrust of thrust schedule A, does not appear advantageous because the climb time is reduced only about 1 minute, the fuel used is increased by more than 3 percent of mission fuel, and the distance toward destination is decreased by 8 to 11 nautical miles.

Domestic climb-corridor operations from JFK have been shown to be advantageous to the air traffic controller in reducing the time required in handling the SST in the congested airspace below FL 400 and to the aircraft operator in appreciable savings in fuel and time. Furthermore, climb-corridor operations would considerably reduce the time

spent in terminal area maneuvering as previously discussed. Most of the pilots commented that consideration should be given to the use of a climbout corridor for the SST so as to avoid large turns at low altitudes, penalties of long radar vectors, and altitude-restricted flight under inbound traffic.

ATC Communications Workload

The percent of time spent on ATC communications in departure and arrival operations was analyzed to illustrate the crew workload involved with ATC communications for the simulated operations of the SST in the present-day ATC system. The time spent on ATC communications was taken as the time spent in transmitting and receiving messages and does not include the time spent in waiting for a clear channel. Only the messages during flight operations were included; that is, for the departures, the messages between and including clearance for take-off and reporting cruise conditions, and for the arrivals, the messages between and including the entry-position report and touchdown-on-the-runway report. The messages involved position and altitude reports; communication frequency-change and speed-change requests; take-off, altitude, route, and IFR clearances; radar vectors; weather and runway-in-use information; and identification confirmation. Results of this analysis for New York domestic departure and arrival operations on both standard and PND routes are given in figure 25.

For the departures on SID routes (fig. 25(a)), the time spent on ATC communications varied from about 5 to 20 percent for the entire departure with an average of 12 percent. The breakdown of the analysis into time intervals after the start of the take-off run shows that the average and the maximum values of ATC communication time are highest for the first 10-minute interval and decrease in succeeding time intervals. The average values of time spent on ATC communications on the PND routes were found to be only a few percent less than the values of time spent on the standard routes for the entire departure and each of the time intervals. An analysis indicated that the only messages eliminated to any extent on the PND routes were radar-vector instructions.

For the arrivals on the standard routes (fig. 25(b)), the time spent on ATC communications varied from about 13 to 31 percent for the entire arrival with an average of 18 percent. The average and the maximum values were lowest for the 20- to 30-minute interval prior to touchdown and increased in succeeding time intervals as touchdown was approached. The high maximum value (53 percent) in the 0- to 10-minute interval was associated with an approach in which an unusual amount of radar vectoring (for traffic separation purposes) was performed. The high maximum value (50 percent) in the 10- to 20-minute interval occurred on one arrival which involved increased communications caused by a pilot error in changing radio frequency. On the PND arrival routes, the average values of time spent on ATC communications were 4 to 6 percent less than on the standard routes. As was the case for the departures, the only messages eliminated

to any extent on the PND routes were radar-vector instructions. The relatively high average values for both standard and PND routes for the entire arrival compared to the averages for the 10-minute intervals resulted from the occurrence of a number of messages in the time period between the entry-position report and 30 minutes prior to touchdown. These messages included the entry-position report, clearance instructions, speed-reduction and descent-initiation reports, and handoff and reclearance instructions.

The SST workload was also examined for comparison with subsonic-jet-transport operations by totaling the number of navigation and communication messages received and transmitted, and the number of transponder switching operations required in 10-minute intervals during arrivals and departures. The workload based on the same analysis was measured for subsonic jet transports during scheduled flight operations into and out of JFK. A comparison of the results is given for arrivals in figure 26. The results indicate that, in the time periods 30 to 20 minutes and 20 to 10 minutes before touchdown, the SST workload is greater than that for the subsonic-jet-transport operation. The greater distances and altitude ranges which the SST passes through in these time periods compared with the subsonic jet transport increases the number of operations per time period. For the period of 10 minutes prior to touchdown, the SST and the subsonic jet transport cover essentially the same distance and altitude range and thus have comparable workloads. During departures, the workload based on a similar analysis was found to be about the same for the SST as for the subsonic jet transport.

For the most part, no adverse comments were made by the airline crews relative to workload for the operations of the SST in the present-day ATC system. However, some pilots indicated that they considered the workload for the SST operation about the same as for present-day subsonic-jet-transport operations which they considered too high. Two pilots emphasized that the peak ATC communications workload, which occurred in the first few minutes after take-off, often coincided with the peak navigation workload, which resulted from low-altitude turns required to avoid penetration of buffer airspace between airports and from restrictions on climb-out operations for flight under arrival traffic and for crossing of airways. Climb-corridor-type operations, as discussed previously, would relieve this problem.

Penalties of Operation in the ATC System

Maneuver time and fuel.- The range and average values of maneuver time and fuel used in the departure and arrival operations at JFK and SFO in the present-day ATC system are shown in figure 27. Maneuver time and fuel are defined as the additional time and fuel used above the time and fuel required for an unrestricted straight climbout or descent, and, hence, indicate the penalties of altitude restrictions connected with traffic separation and with ATC handoff procedures, of radar vectoring around buffer zones and other traffic, of arrival and departure maneuvering to and from the runways in use, and

of indirect routings required in the use of the airways system. Also shown is the contingency fuel allowance (7 percent of mission fuel) provided by the standards of reference 8. (Mission fuel is defined in the appendix.)

For the standard departures (fig. 27(a)), the maneuver times averaged 2 minutes or less for JFK oceanic and SFO domestic operations. These situations involved fairly straight routings and a minimum of altitude restrictions, although values between 4 and 5 minutes were also experienced. For JFK domestic operations, however, the maneuver time averaged nearly 5 minutes with values to 6.5 minutes. These higher values reflected the considerable amount of eastward and southward or northward flying required before westward headings could be flown. (See figs. 14(c) and 14(d).) The corresponding maneuver-fuel results show that the maneuvering for JFK domestic operations resulted in use of from 1.3 to 4.0 percent of mission fuel. An average of 2.8 percent of mission fuel was used in these operations, an amount equal to 40 percent of the contingency fuel allowance. In a few tests, the maneuver fuel used was reduced on the average by 1.7 percent of mission fuel (24.3 percent of the contingency fuel allowance) by delaying application of maximum augmented thrust during climbout from FL 190 to FL 310 with the penalty, however, of an increase in block time of 1.7 minutes.

In contrast to the JFK domestic departures, the maneuver fuel used in the SFO domestic departures was considerably smaller because of the effect of the smaller maneuver times and the infrequent altitude restrictions at SFO; the average maneuver fuel used in the SFO domestic departures was only 0.7 percent of mission fuel. The rather extreme range of values and high average value of maneuver fuel for the JFK oceanic departures resulted from a number of factors which existed in these operations: namely, (1) lack of good vertical-profile guidance, (2) use of climb speeds below optimum, (3) assignment of a variety of cruise altitudes, and (4) use of a turbojet engine more sensitive to off-optimum operations than the turbofan engine used in the domestic operations. The oceanic-departure maneuver-fuel results are, therefore, more indicative of departure fuel use which involves nonoptimum operations as well as ATC penalties.

Maneuver time and fuel used in some special departure operations are given in figure 27(b). The JFK experimental departures were special tests to study the effects of postponing supersonic flight until the SST was on a straight-line route toward destination. The SFO domestic military-block departures were special tests to study the effects of having to overfly airspace allocated temporarily to military operations. Descriptions of the procedures used in these tests are given in previous sections.

The maneuver time for the JFK experimental departures averaged 8.5 minutes, an increase of 3.7 minutes over the average time for standard JFK domestic departures. The increased time over the standard departures resulted from the decrease in average flight speed due to the prolonged subsonic flight time. The maneuver fuel used in the

experimental departures averaged 1.7 percent of mission fuel, which was substantially less than the average maneuver fuel used in standard JFK domestic operations. These results indicate that only by a substantial increase in block time can the penalty of high maneuver-fuel use (as well as the problems of turning at transonic speeds as previously discussed) be nullified for domestic departure operations from New York with present-day ATC system procedures.

A comparison of the maneuver time and fuel values shown in figure 27(b) for the SFO domestic military-block operations and the standard SFO domestic departures shows the penalties of having to fly westward (before turning eastward) to gain sufficient altitude to overfly the blocked airspace. On the average, an additional 1.9 minutes was used as a result of the approximately 65 additional miles flown. The additional penalty in fuel averaged 2.2 percent, an amount equivalent to 31.4 percent of the contingency fuel allowance. This relatively high penalty in fuel for the small increase in maneuver time is associated with the increase in the length of the cruise phase of the mission. This increase in the length of the cruise phase resulted from the initial westward deviation. A lengthening of the cruise phase from such a deviation is costly in fuel because the cruise fuel rate is high; that is, about 0.9 percent of mission fuel per minute. The lengthening of the cruise phase is not, however, particularly costly in time because the time is made up at the cruise rate. It is emphasized that the time and fuel penalties shown for the SFO domestic military-block operations are those in addition to the ATC penalties for standard SFO domestic departures.

For arrival operations at JFK and SFO, maneuver times and fuel are given in figure 27(c). Maneuver times for arrival operations at JFK and SFO were found to be higher in each case than the corresponding departure operation. (Compare with fig. 27(a).) For domestic and oceanic arrival operations at JFK, average maneuver times of 8.6 and 6.6 minutes, respectively, were measured. These high values result from the substantial distance required to be traversed at slow speeds from the Deer Park (DPK) and Colts Neck (COL) holding points (fig. 12(b)) and from a considerable number of altitude restrictions during descent. Because of the shorter distances from the San Jose and Woodside holding points (fig. 12(d)) and fewer altitude restrictions during descent the maneuver times for the SFO domestic arrivals averaged only 2.8 minutes. The corresponding maneuver-fuel results similarly show on the average higher values for the JFK domestic and oceanic arrival operations than for the SFO arrivals; average values of 2.7 and 2.3 percent, respectively, were measured at JFK in contrast to an average value of 1.0 percent at SFO. For the JFK domestic arrivals, the average maneuver fuel used is equal to 38.6 percent of the contingency fuel allowance. The importance of closely timing the initiation of slowup for descent was noted in two JFK domestic arrivals in which thrust reduction to the flight-idle condition was performed 2 minutes early. The

resulting increase in slow-speed, low-altitude operations increased the maneuver time about 4 minutes and the maneuver fuel about 0.5 percent of mission fuel over the average results shown.

In summary, departure and arrival operations for the SST in the New York terminal area were found to use considerable amounts of fuel for maneuvering because of lengthy indirect routings and altitude restrictions for traffic separation and controller handoff procedures. Departure and arrival operations in the San Francisco terminal area were found to require smaller amounts of fuel for maneuvering. Because the current standards (ref. 8) do not require fuel to be carried for terminal area maneuvering, the fuel used in terminal area maneuvering is assumed to be drawn from the en route contingency fuel allowance. On this basis, domestic operations at New York consumed on the average 40 percent of the en route contingency fuel allowance in departures and 38.6 percent in arrivals. Domestic operations at San Francisco consumed on the average 10 percent of the en route contingency fuel allowance in departures and 14.3 percent in arrivals. A military-block operation affecting departure routing at San Francisco resulted in an average additional fuel usage equivalent to 31.4 percent of the contingency fuel allowance.

Effects on mission.- The effects of operations in the present-day ATC system on mission fuel requirements and block speed are given in figure 28. Block speed is the average speed based on the great circle distance for the mission and time required from take-off to landing. The range of values of mission fuel and block speed shown by the shaded areas were obtained by combining the extreme fuel and time values measured in the departure and arrival operations in the present tests with calculated cruise values of fuel and time. Thus, these results represent the extremes in mission fuel and block speed which could be encountered for operations in the present-day ATC system for conditions of no holding and no deviations in cruise. The transcontinental mission was assumed to be 2500 nautical miles, and the transatlantic mission, 3160 nautical miles. Cruise at a Mach number of 3.0 was assumed. A cruise fuel rate of 55 pounds (25 kilograms) per nautical mile was used. The calculated values of mission fuel and block speed, as shown by the dashed lines, were obtained by combining measurements of fuel and time in unrestricted straight climbouts and descents with calculated cruise values of fuel and time. These results thus serve as a basis for the assessment of the effects of the ATC system on mission fuel and block speed. Calculated values of mission fuel and block speed for subsonic jet missions of the same length (solid lines), based on the data in reference 9, are also shown for comparative purposes.

The mission fuel results given in figure 28 are presented as a percentage of the fuel required to cruise the total distance (hereinafter referred to as over-to-over cruise fuel). In this form, the amount of mission fuel used above 100 percent shows the effects of the fuel used in climbout and descent on the mission fuel requirements; that is, the

combined fuel requirements for starting and stopping and for ATC deviations. As shown by the measured values (shaded areas), the SST mission fuel for operations in the ATC system ranged between 129 and 136 percent of over-to-over cruise fuel for a transcontinental mission and between 122 and 131 percent for a transatlantic mission. The 5- to 7-percent higher values of mission fuel measured for the transcontinental mission compared to the transatlantic mission result from the increased effects for a shorter mission of the operating costs of starting and stopping and ATC deviations. Because the calculated mission fuels for the two missions (dashed lines) do not include ATC penalties, the penalty for starting and stopping can be seen to be 4 percent greater for the shorter mission by a comparison of these calculated values. As can be seen from the difference in the calculated mission fuels for these two missions, the operating cost of starting and stopping is 4 percent greater for the shorter mission. Thus, the ATC penalties are apparently from 1 to 3 percent of over-to-over cruise fuel greater for the shorter mission. The calculated values of mission fuel for comparable subsonic-jet-transport missions (solid lines) are seen to be considerably lower than for the SST and indicate only a 2-percent effect for the shorter mission on the cost of starting and stopping.

The block-speed results given in figure 28 are presented in percentage of cruise speed. The amount of block-speed decrement below 100 percent thus shows the combined effects of starting and stopping and ATC deviations. As shown by the measured values (shaded areas), the block speed ranged between 63 and 70.5 percent of cruise speed for a transcontinental mission and between 71 and 79 percent for a transatlantic mission. The increased effects for the shorter transcontinental mission of starting and stopping and ATC deviations are thus seen to be 8 or 9 percent of cruise speed. Because the calculated block speeds for the two missions (dashed lines) do not include ATC penalties, the penalty for starting and stopping can be seen to be 5 percent greater for the shorter mission by a comparison of these calculated values. Thus, the ATC penalties are apparently 3 to 4 percent of cruise speed greater for the shorter mission. The calculated values of block speed for comparable subsonic-jet-transport missions are seen to be much higher than for the SST and indicate only about a 1-percent effect for the shorter mission on the cost of starting and stopping.

These results indicate the increased sensitivity for the SST to starting and stopping and to ATC deviations on mission fuel and block speed compared to subsonic jet transports, especially for the shorter missions.

CONCLUDING REMARKS

Results of an investigation of the problems for the supersonic transport (SST) encountered in simulated operations in the present-day air traffic control (ATC) system are presented. The studies were conducted in real time by using an SST aircraft flight

simulator and the Federal Aviation Administration (FAA) ATC simulation facilities. The aircraft flight simulator was operated by airline crews and the ATC simulation facilities were operated by experienced air traffic controllers. Design study configurations of the SST were used in the tests. The test program included departures and arrivals under weather conditions which required operation by FAA Instrument Flight Rules in the New York, New York, and San Francisco, California, terminal areas. Some of the principal results from the simulated operations are:

1. On established departure and arrival routes, the SST was required in many instances to make substantial changes in heading at low supersonic speeds. For departures, such turns were detrimental to performance, and provision of straight-line route segments from 120 to 170 nautical miles in length for SST supersonic acceleration were considered to be highly desirable.

2. On the basis of fuel allowances provided under the Tentative Airworthiness Standards for Supersonic Transports (Nov. 1, 1965; Revision 4, Dec. 29, 1967), terminal area maneuvering in the New York area consumed on the average up to 40 percent of the en route contingency fuel in departures and up to 38.6 percent in arrivals.

3. Climb-corridor-type operations for domestic departures from runways 31L and 13R at John F. Kennedy International Airport, New York, were shown to be feasible without violating existing restricted airspace outside the airport area. Such operations reduced the amount of time for the supersonic transport in the congested airspace below 40 000 feet (12.19 kilometers) by approximately one-half and resulted in savings of 1 to 2 percent of mission fuel.

4. Crew workload associated with Air Traffic Control communications and navigation in the present-day Air Traffic Control system was not, in general, enough higher than that for subsonic-jet-transport operations to elicit adverse comments from the pilots.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., February 23, 1968,
720-05-00-04-23.

APPENDIX

DEFINITION OF MISSION FUEL

Mission fuel is the total fuel required for:

(1) Taxiing out
(2) Take-off
(3) Acceleration to climb speed
(4) Departure air maneuver (4 minutes at 250 KIAS at 1500 feet)
(5) Acceleration and climb to initial cruise conditions
(6) Supersonic cruise climb
(7) Deceleration and descent
(8) Destination air maneuver (5 minutes at 250 KIAS at 1500 feet)

REFERENCES

1. Sluka, Andrew L.: A Simulation Study of ATC Procedures for Supersonic Aircraft. Interim Mem. Rep. Proj. No. 101-28X, FAA, Oct. 1963.

2. Hughes, Donald L.; Powers, Bruce G.; and Dana, William H.: Flight Evaluation of Some Effects of the Present Air Traffic Control System on Operation of a Simulated Supersonic Transport. NASA TN D-2219, 1964.

3. Sluka, Andrew L.: ATC Concepts for Supersonic Vehicles – Part I. Rep. No. RD-66-62, FAA, Aug. 1966.

4. Silsby, Norman S.; and Fischer, Michael C.: A Simulator Study of a Pictorial Navigation Display in Instrument Departures of the Supersonic Transport. NASA TN D-4029, 1967.

5. Anon.: ATC Procedures. AT P 7110.1B, FAA, Nov. 12, 1964.

6. Maglieri, Domenic J.; and Lansing, Donald L.: Sonic Booms From Aircraft in Maneuvers. NASA TN D-2370, 1964.

7. Sawyer, Richard H.: A Simulator Study of Airspace Requirements for the Supersonic Transport. NASA TN D-1964, 1963.

8. Anon.: Tentative Airworthiness Standards for Supersonic Transports. Flight Standards Service, FAA, Nov. 1, 1965; Revision 4, Dec. 29, 1967.

9. Nowlan, F. S.; and Comstock, K. W.: The Assessment of Supersonic Transport Operating Costs. Paper 911K, Soc. Automotive Eng., Oct. 1964.

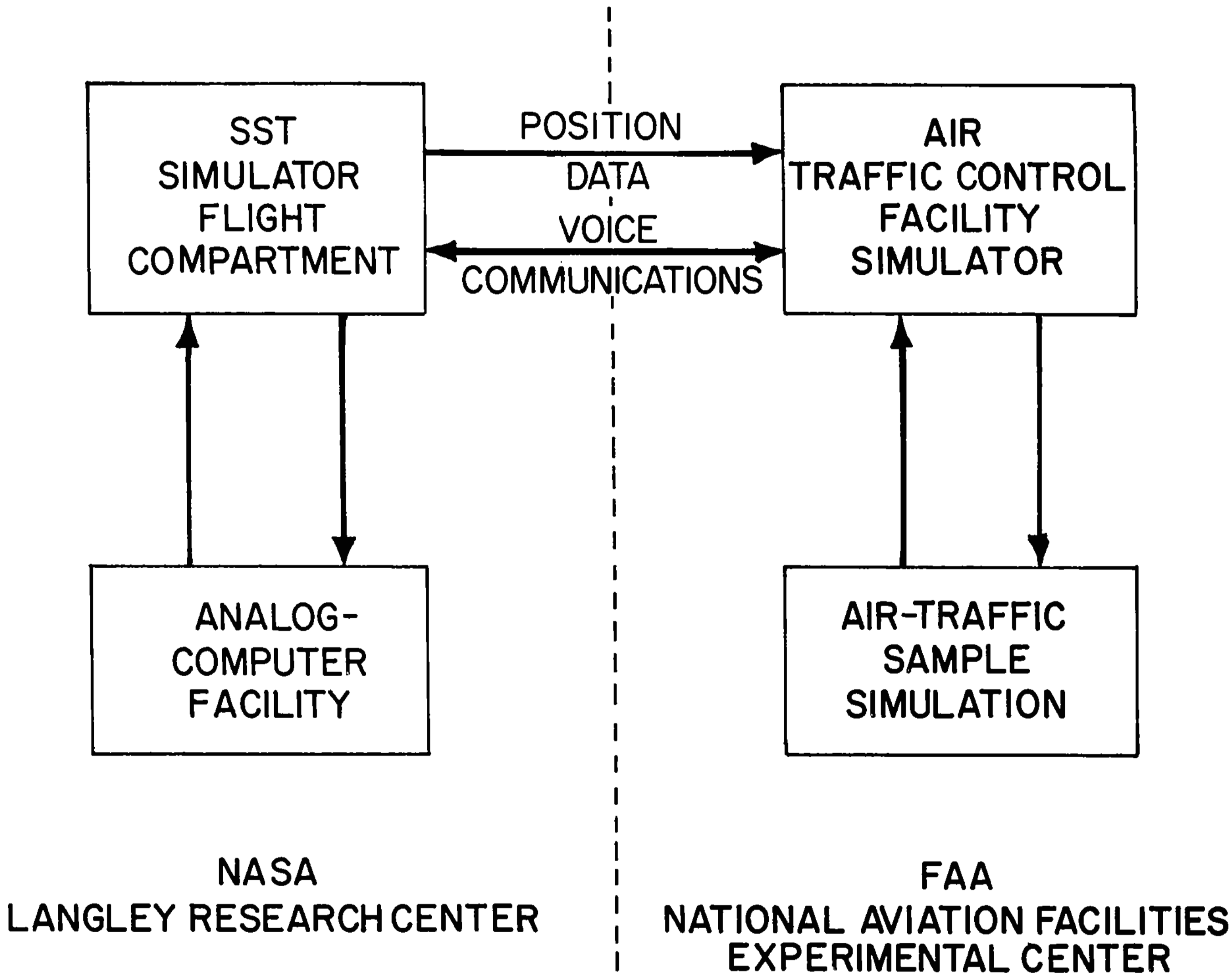


Figure 1.- SST ATC simulation method.

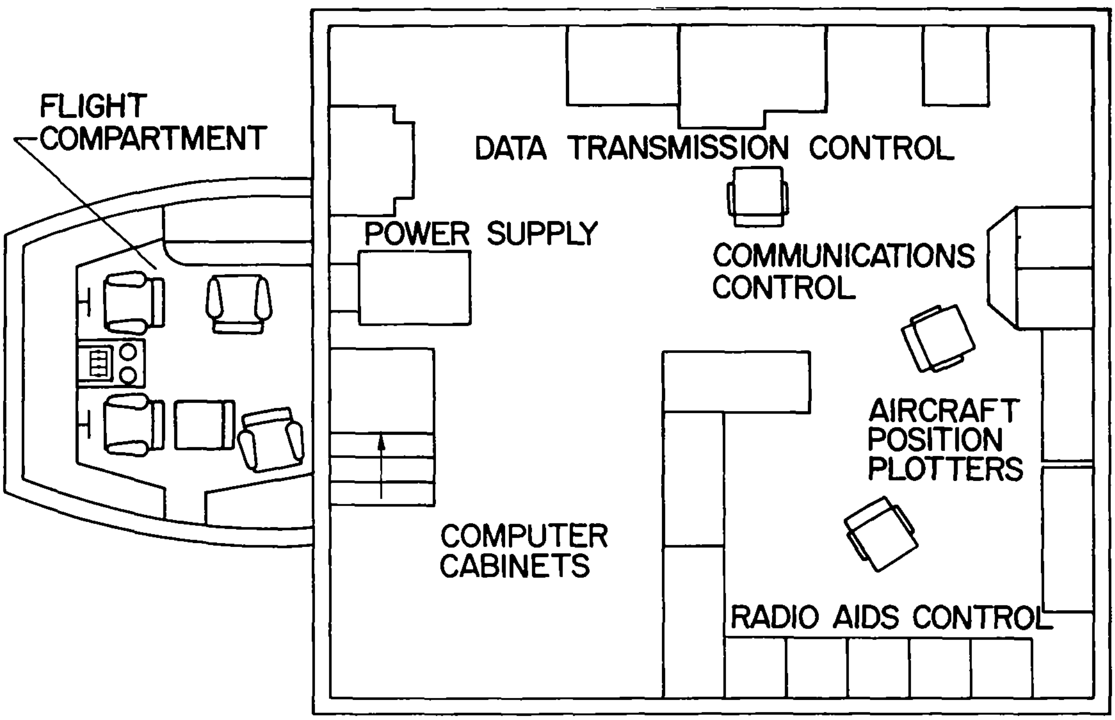


Figure 2.- SST simulator and control room at LRC.

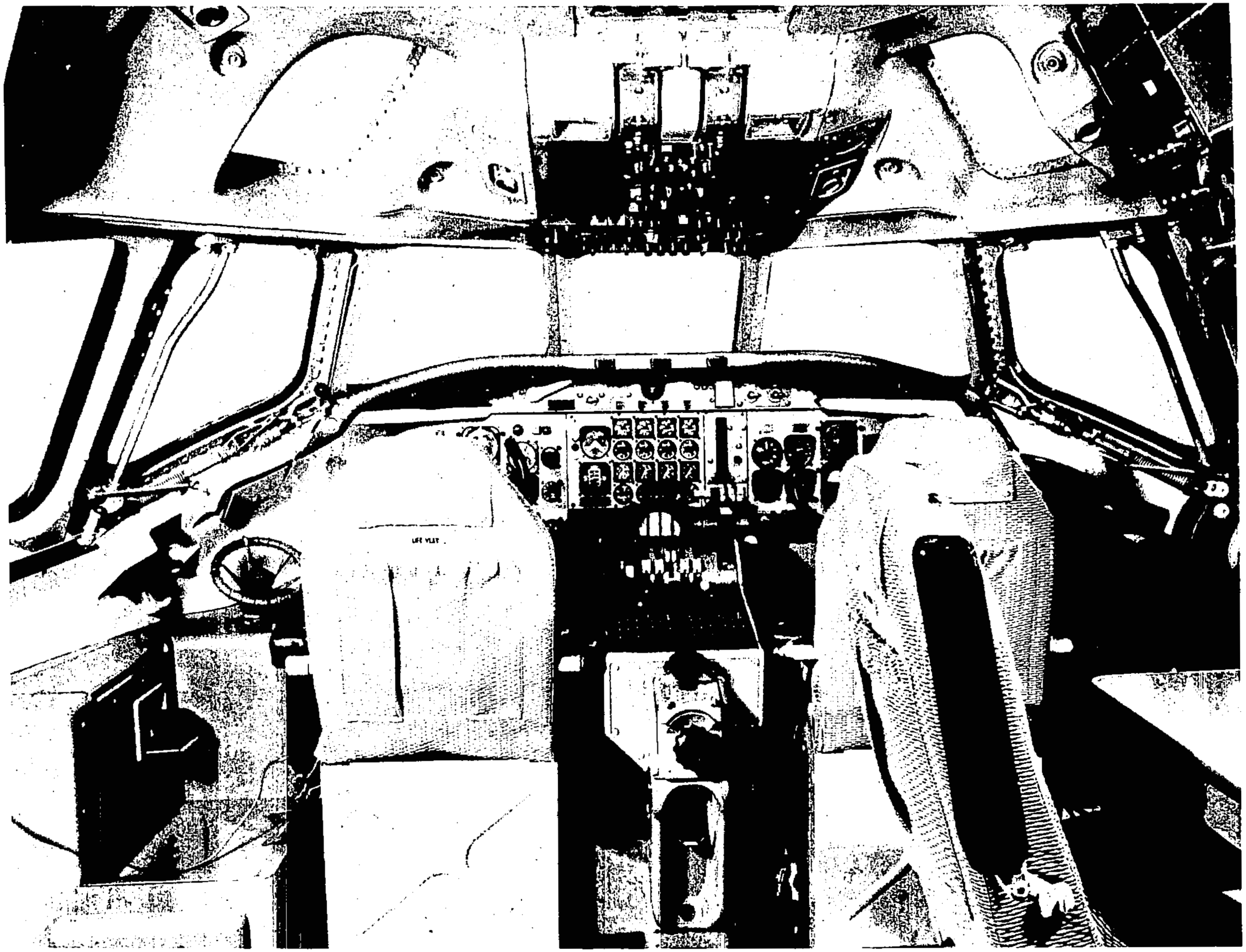


Figure 3.- Fixed-base SST simulator cockpit at LRC. L-68-853

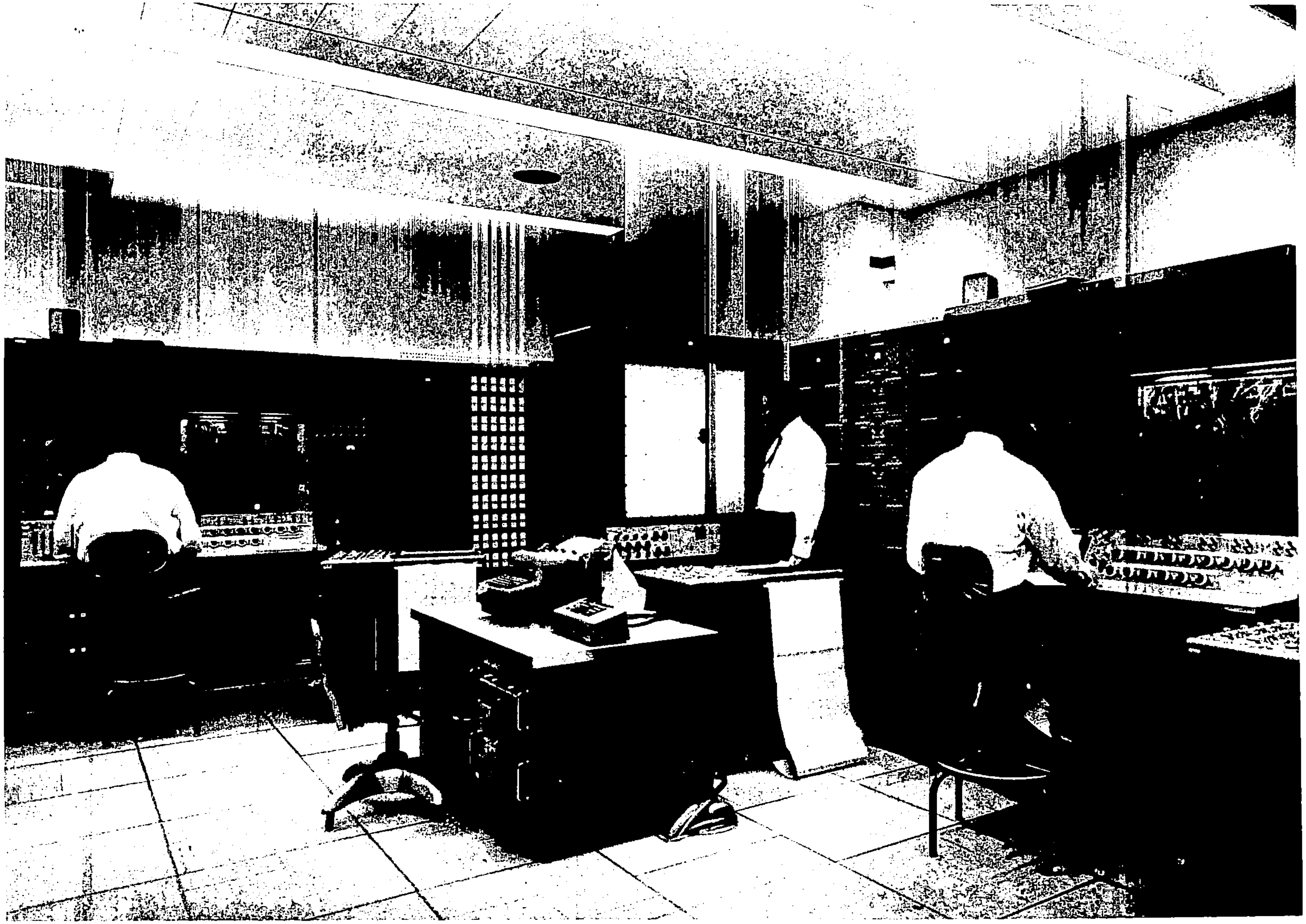


Figure 4.- Analog-computer facility at LRC. L-68-854

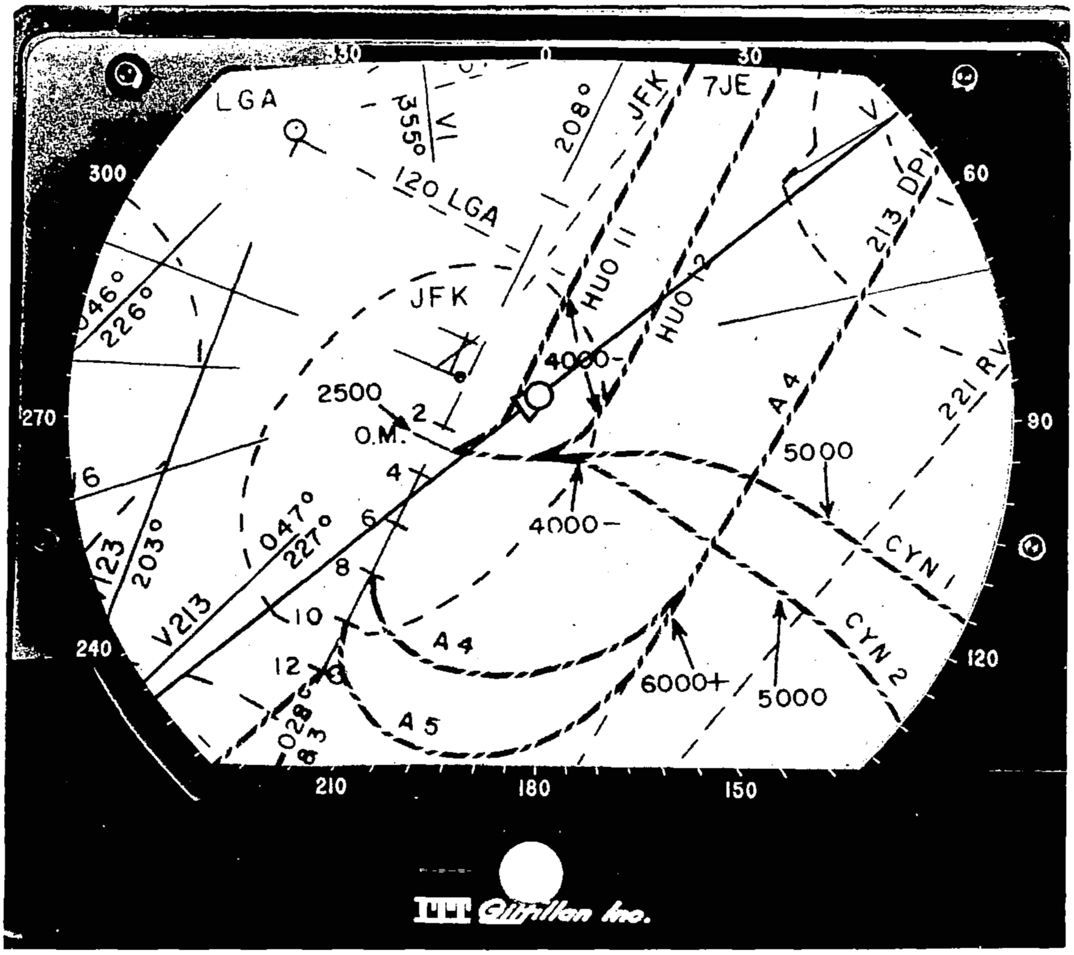


Figure 5.- Pictorial navigation display. (Approx. 2/3 full scale.)

Figure 6.- ATC facility simulator at NAFEC. L-68-855

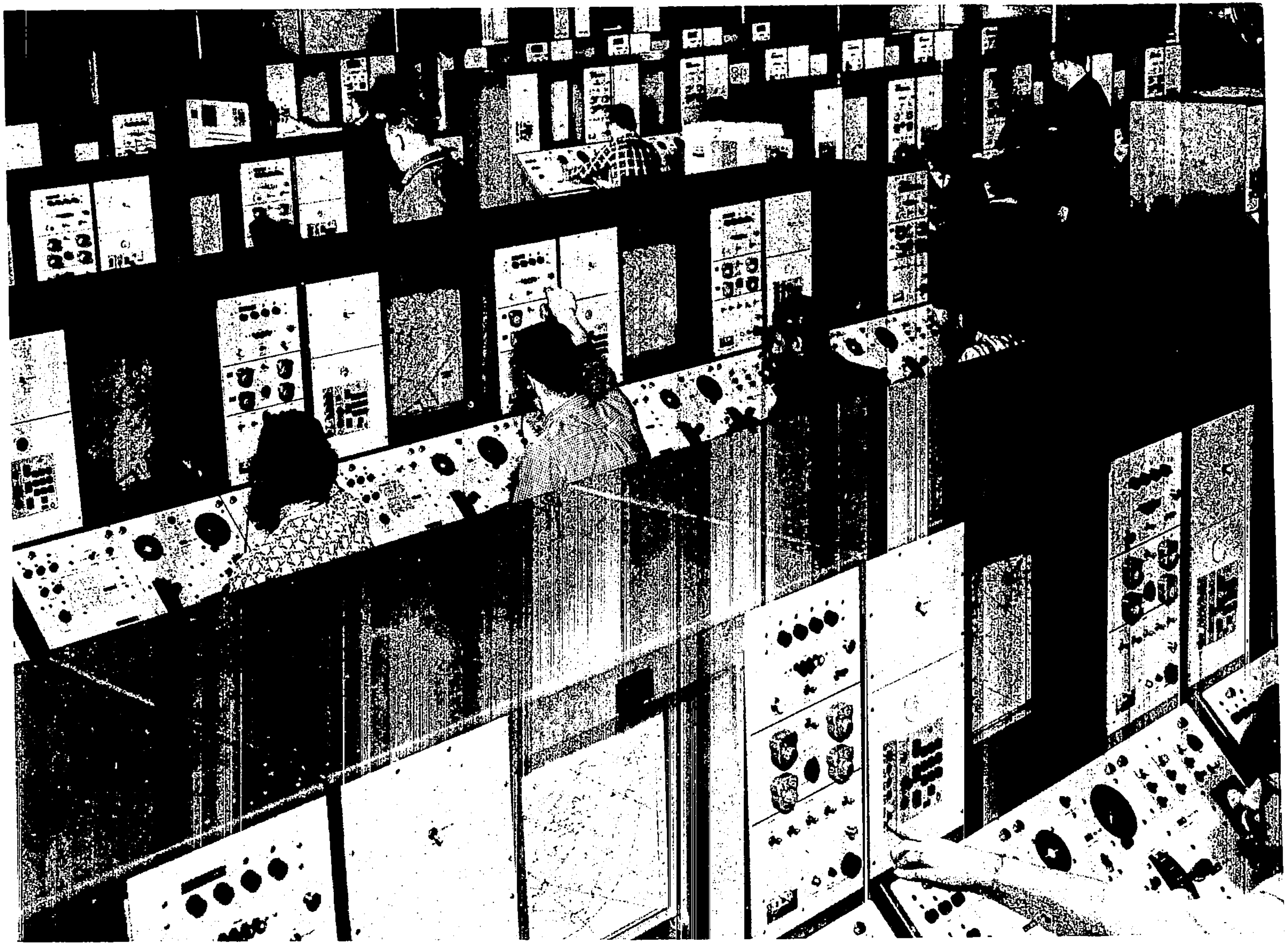


Figure 7.- Radar target generators at NAFEC. L-68-856

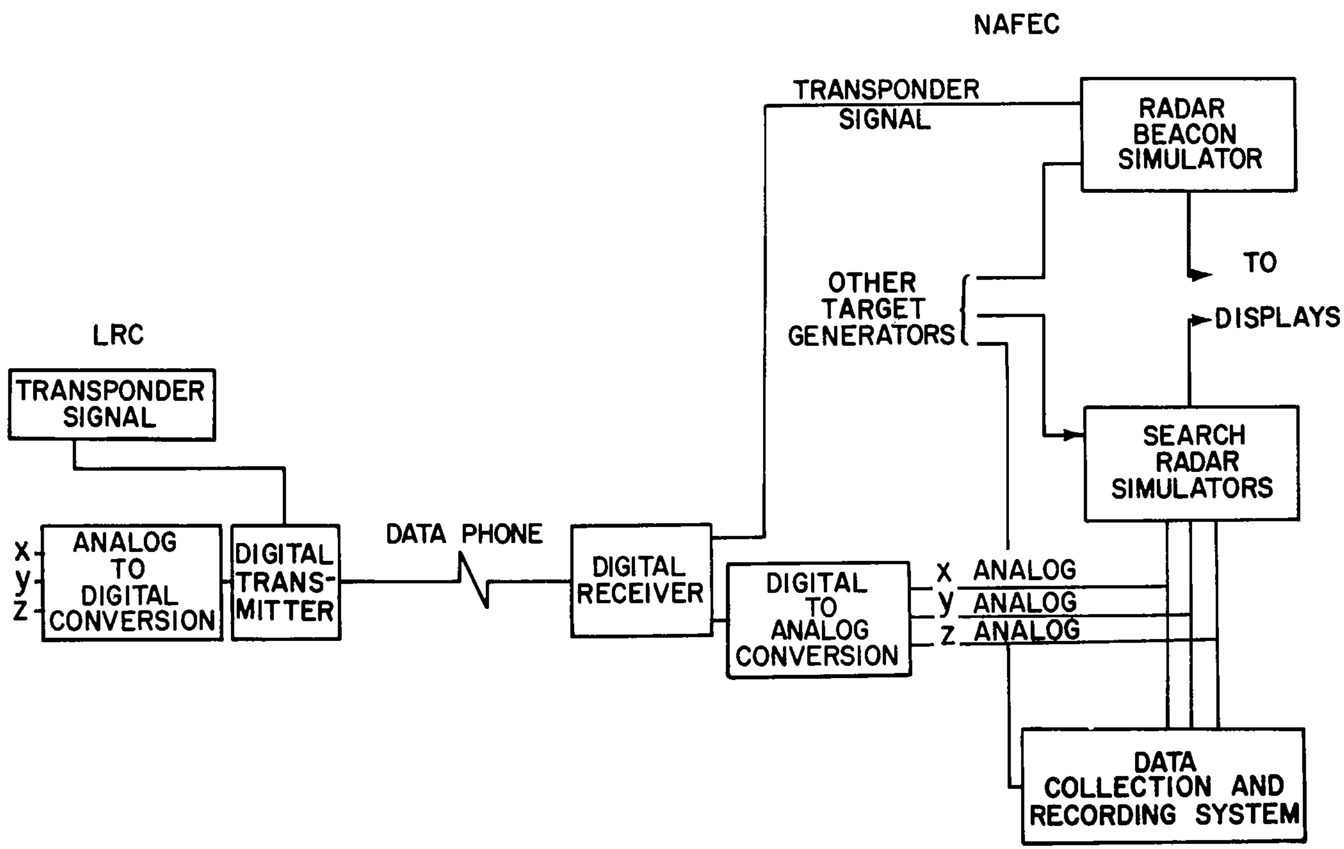
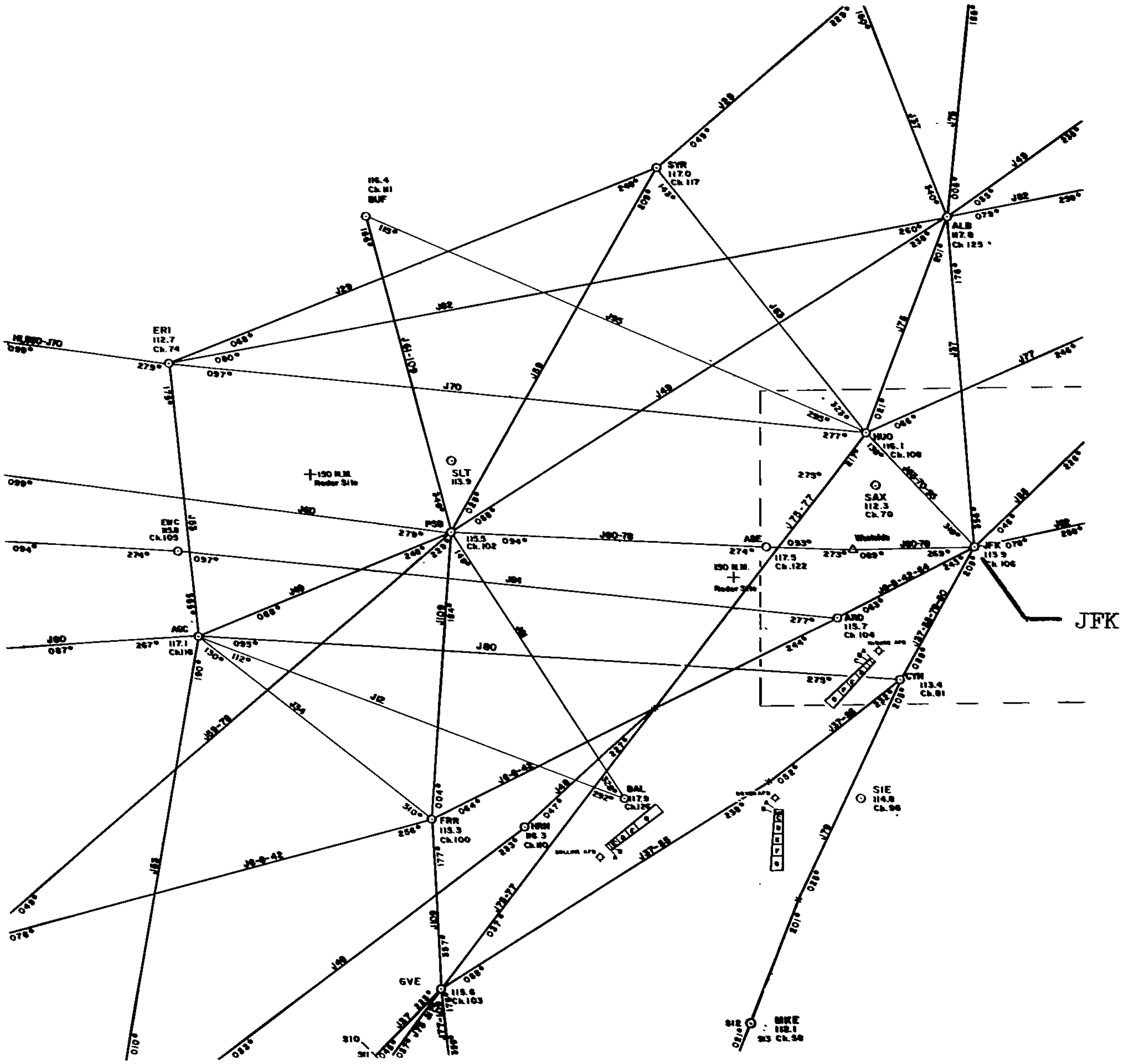
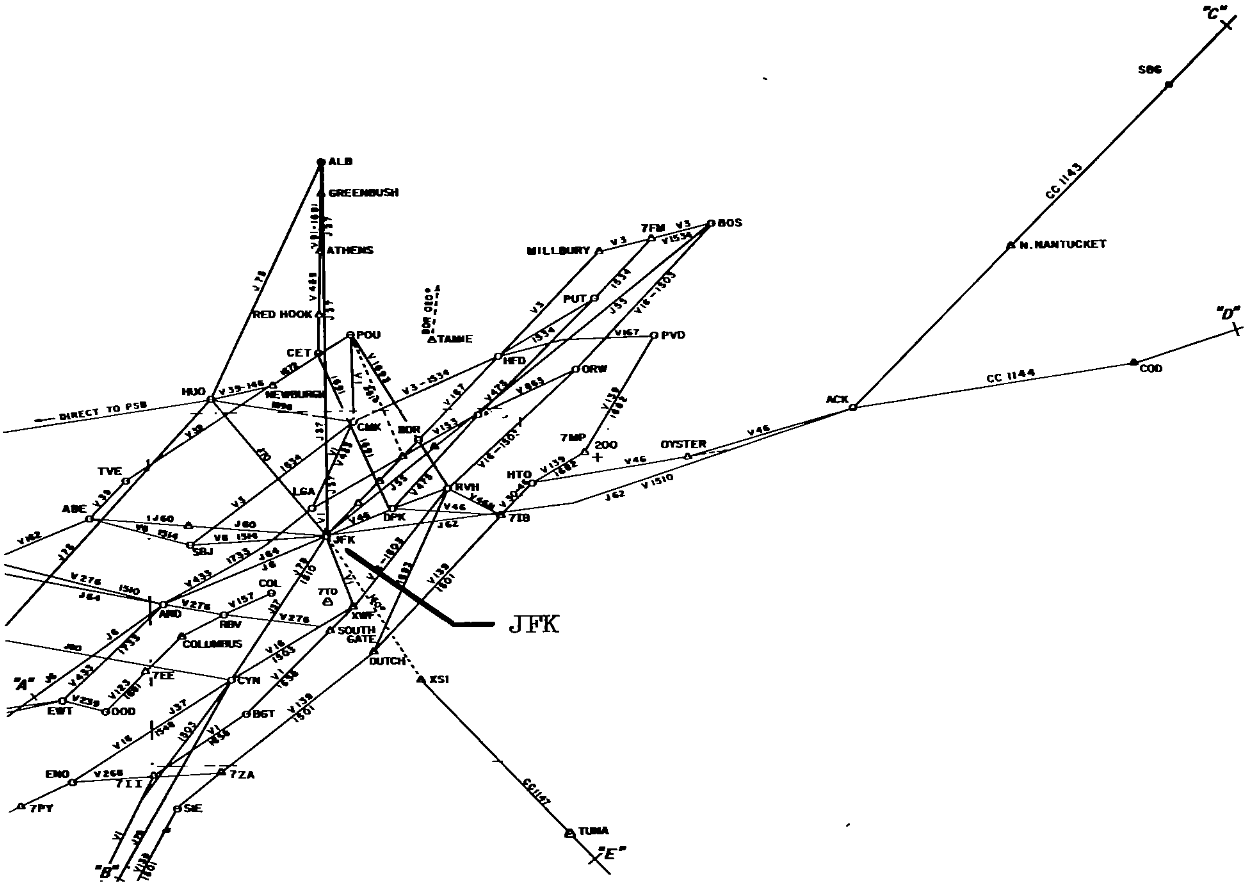


Figure 8.- Data transmission system between LRC and NAFEC facilities.



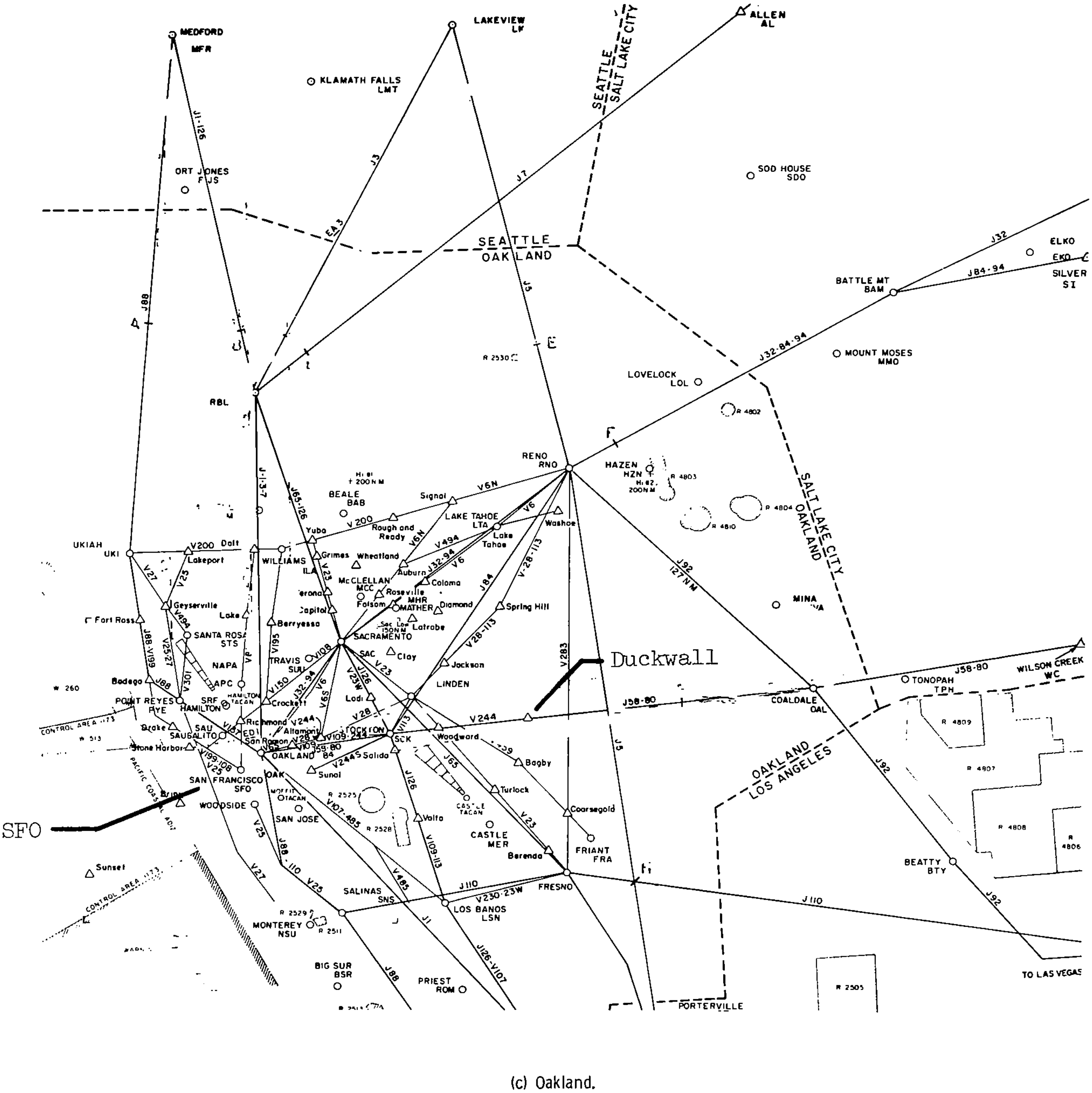
(a) New York domestic.

Figure 9.- Test environments.



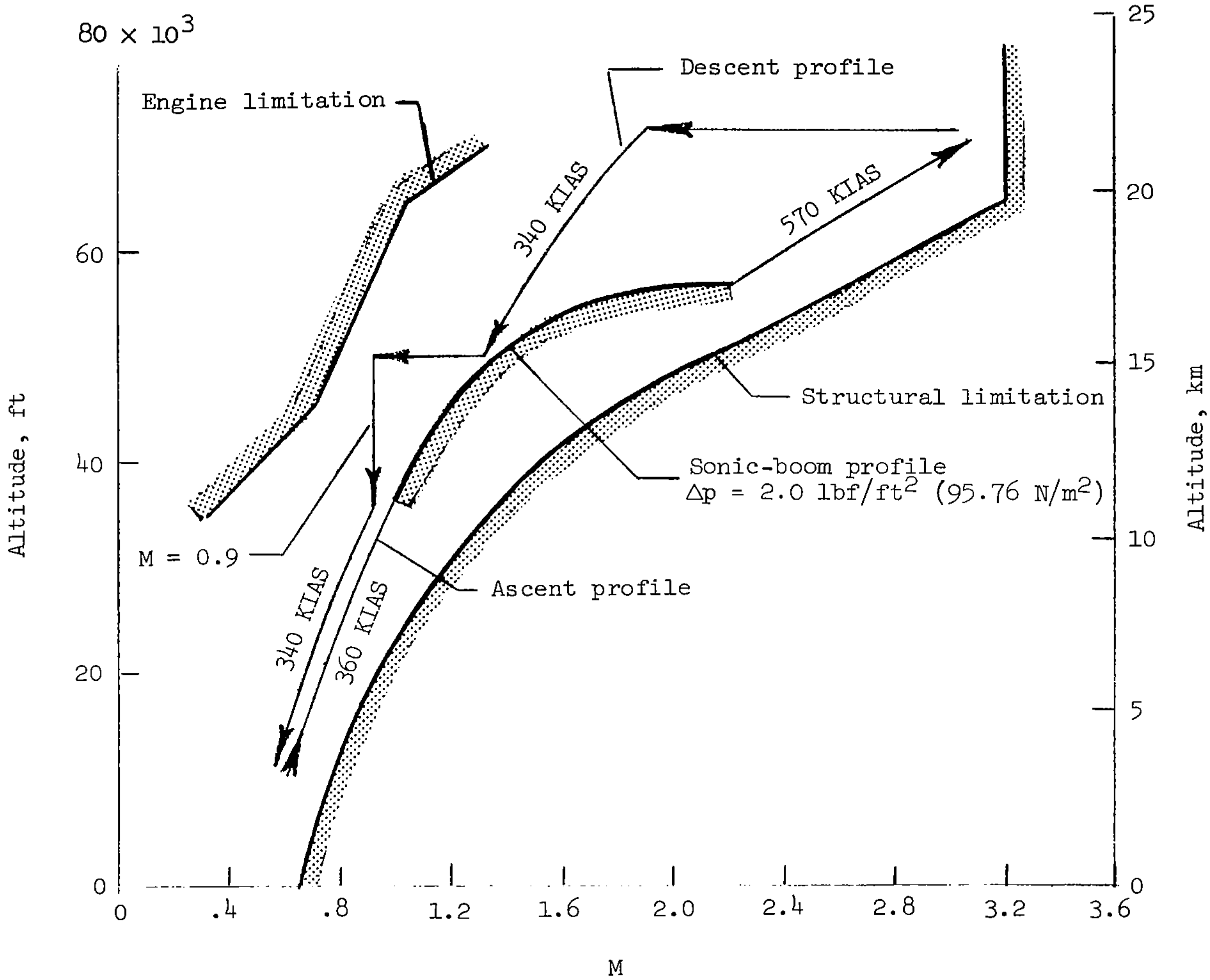
(b) New York oceanic.

Figure 9.- Continued.



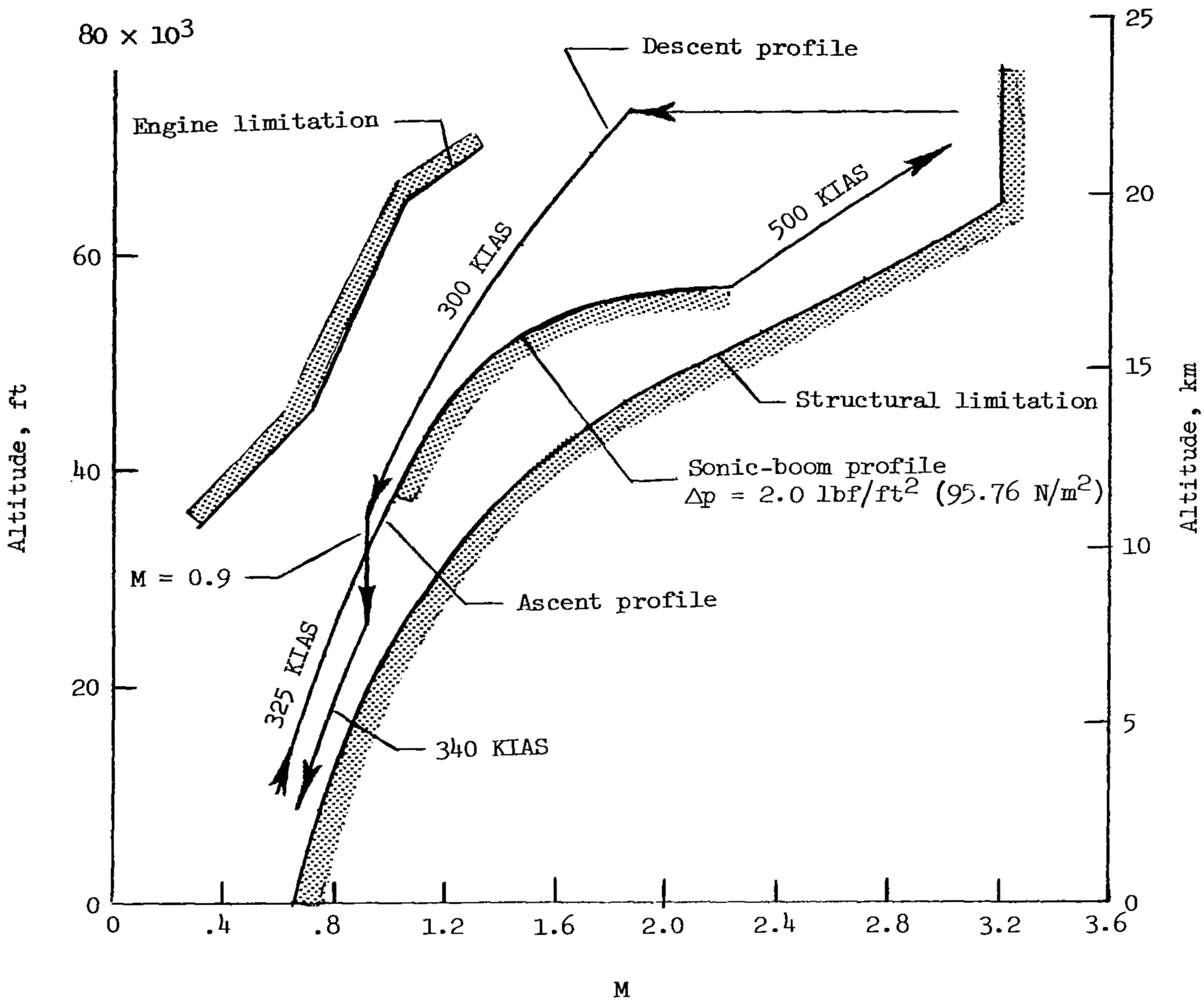
(c) Oakland.

Figure 9.- Concluded.



(a) Configuration A.

Figure 10.- Profiles and limitations.



(b) Configuration B.

Figure 10.- Concluded.

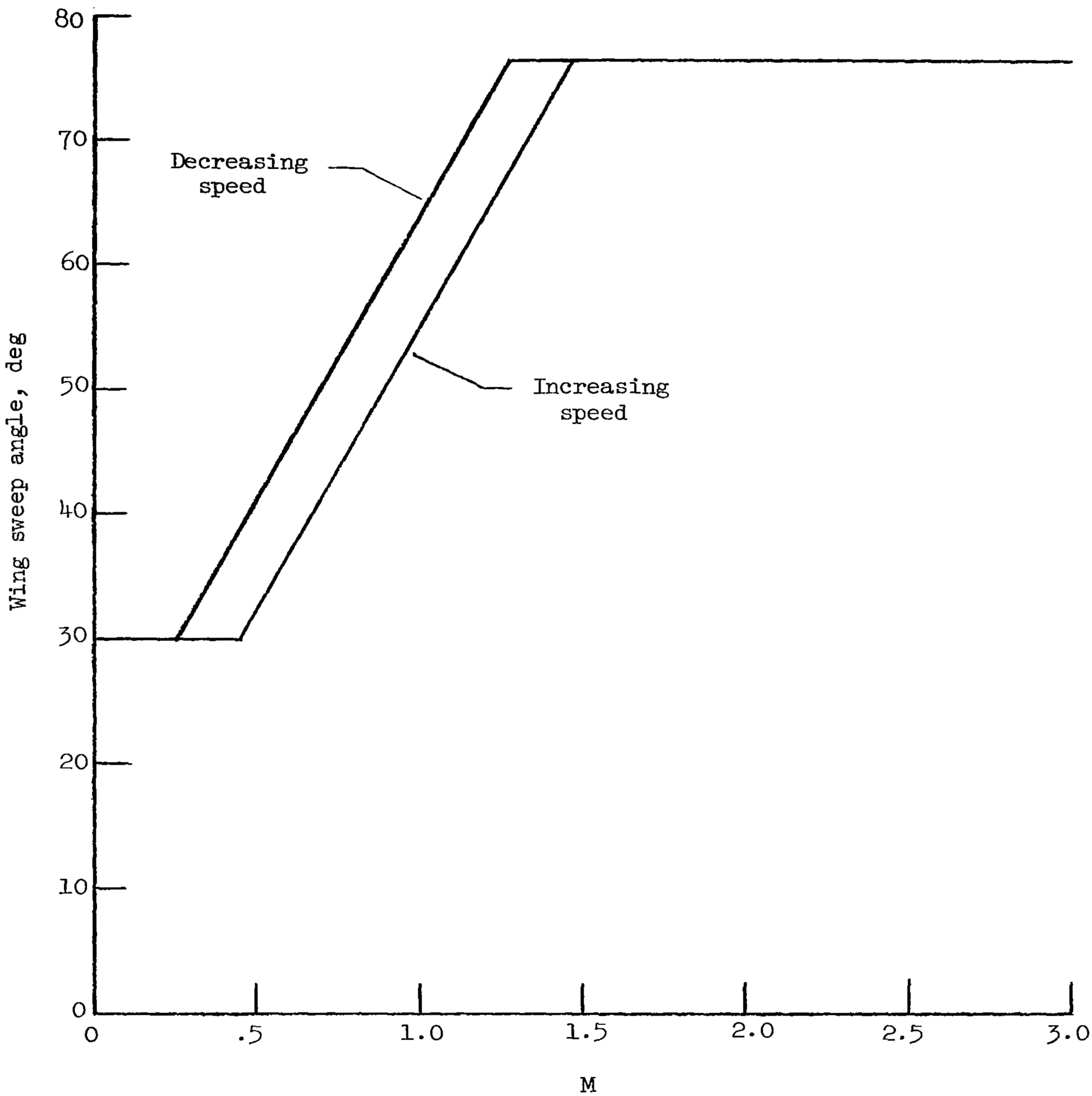
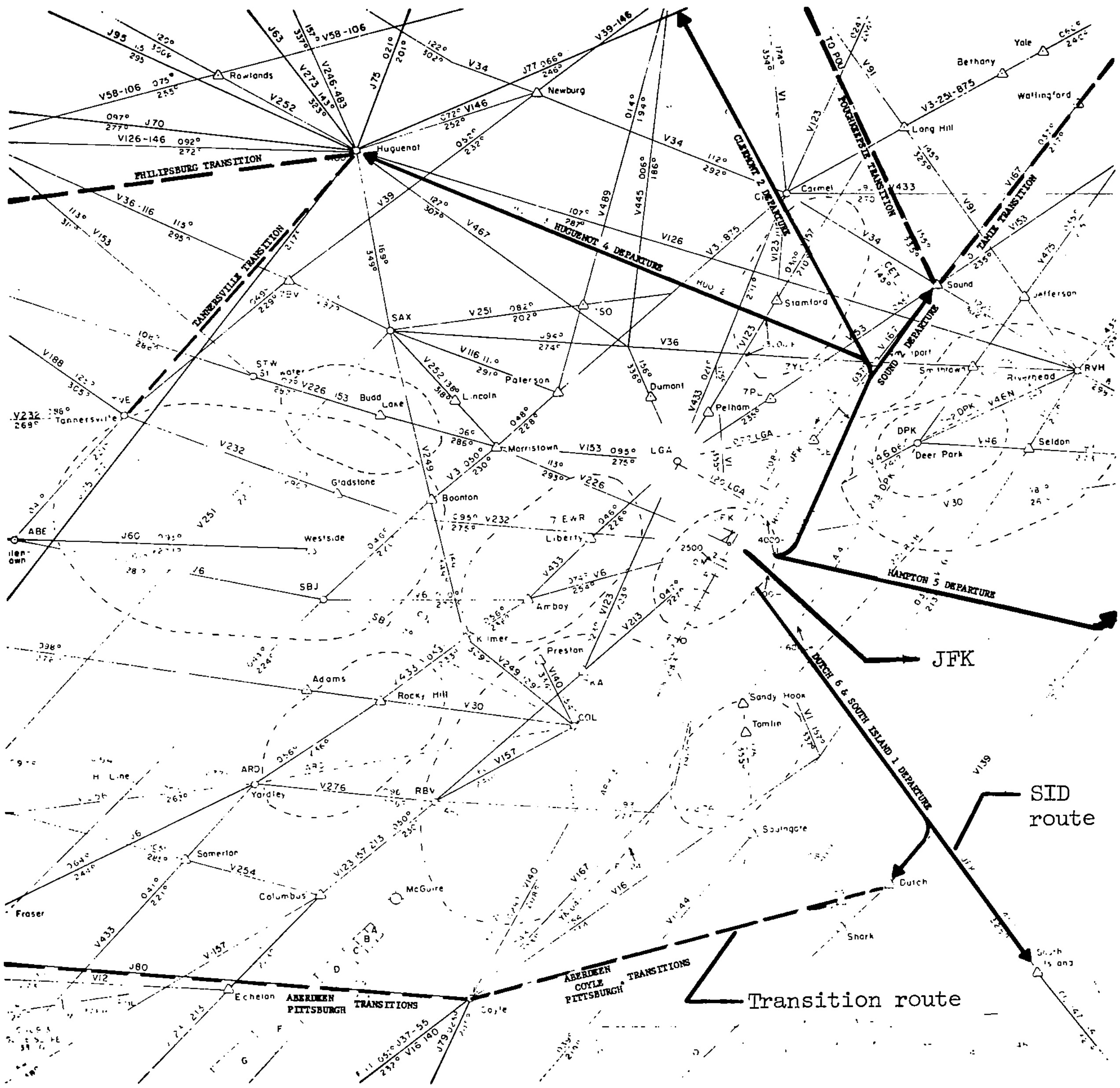
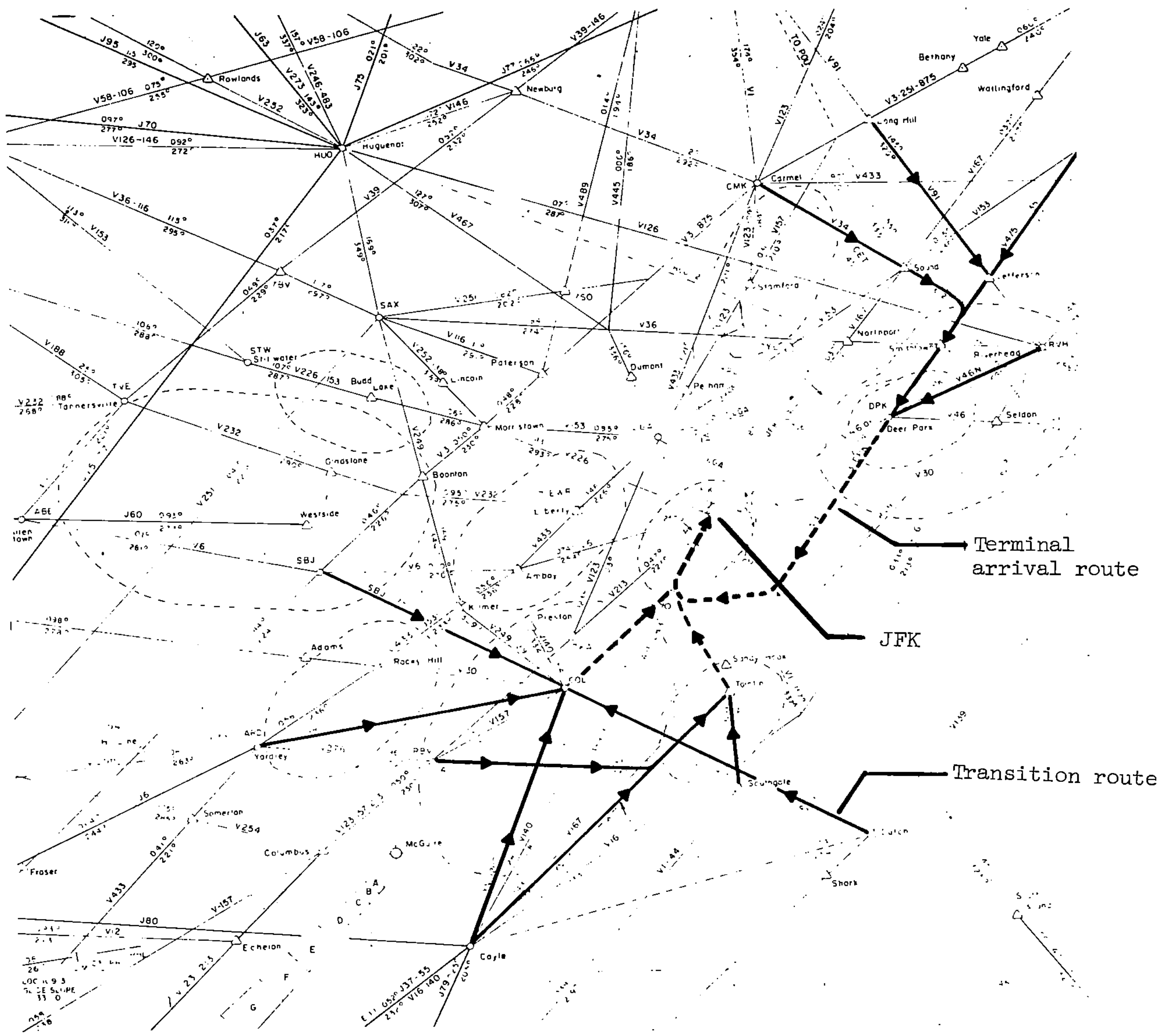


Figure 11.- Wing-sweep schedule for SST configuration A.



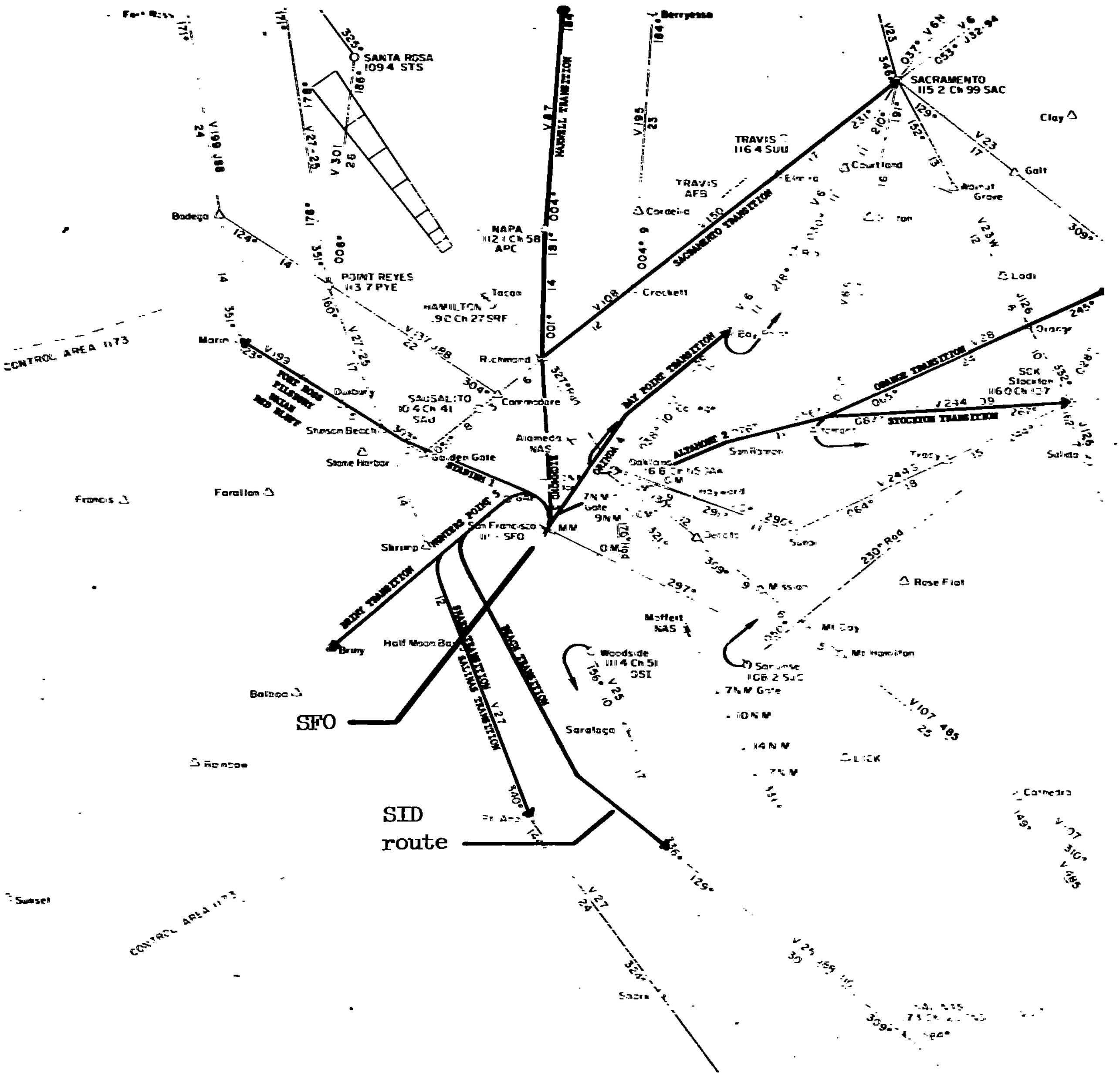
(a) JFK SID routes.

Figure 12.- SID and terminal arrival routes.



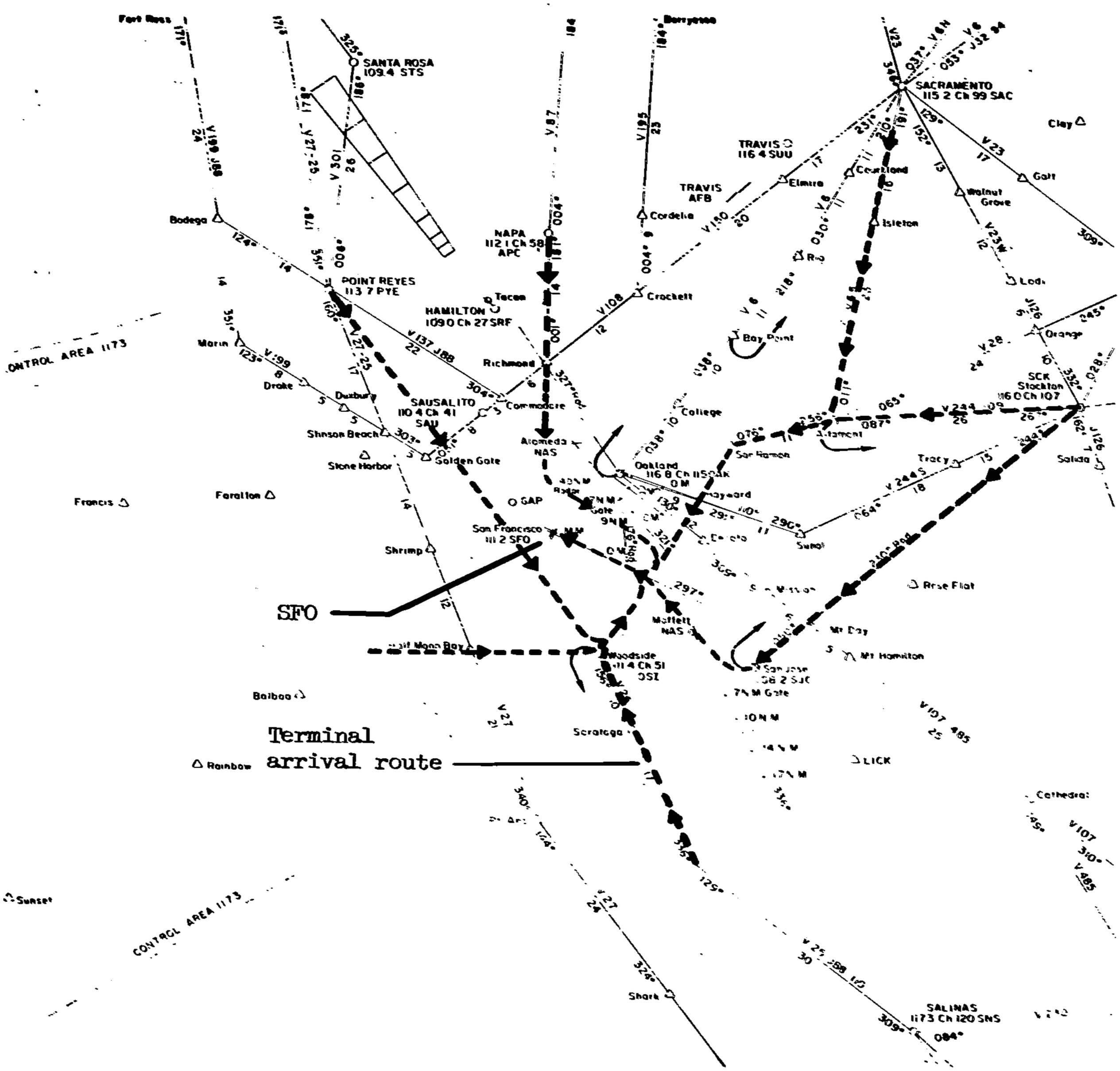
(b) JFK terminal arrival routes.

Figure 12.- Continued.



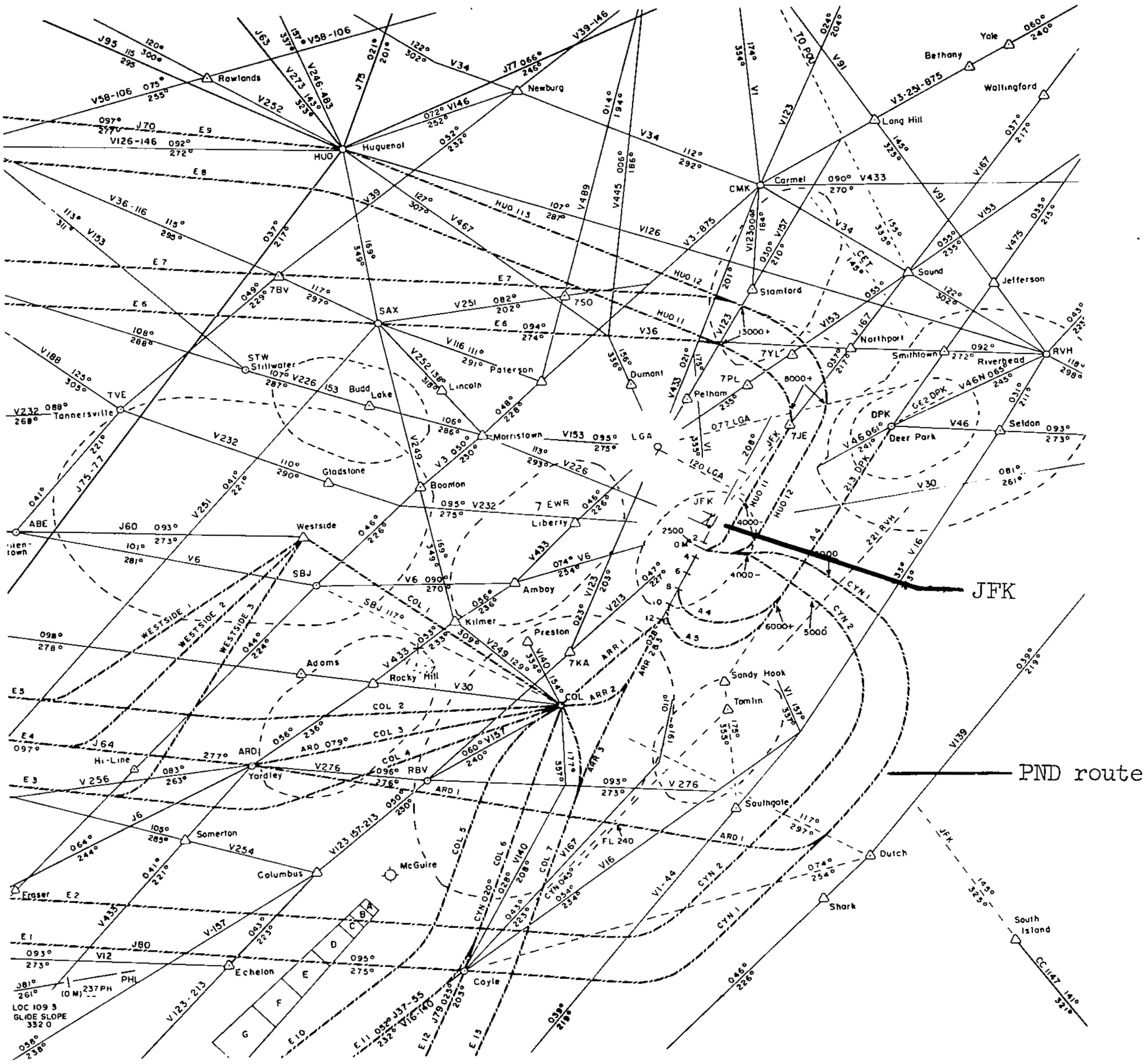
(c) SFO SID routes.

Figure 12.- Continued.



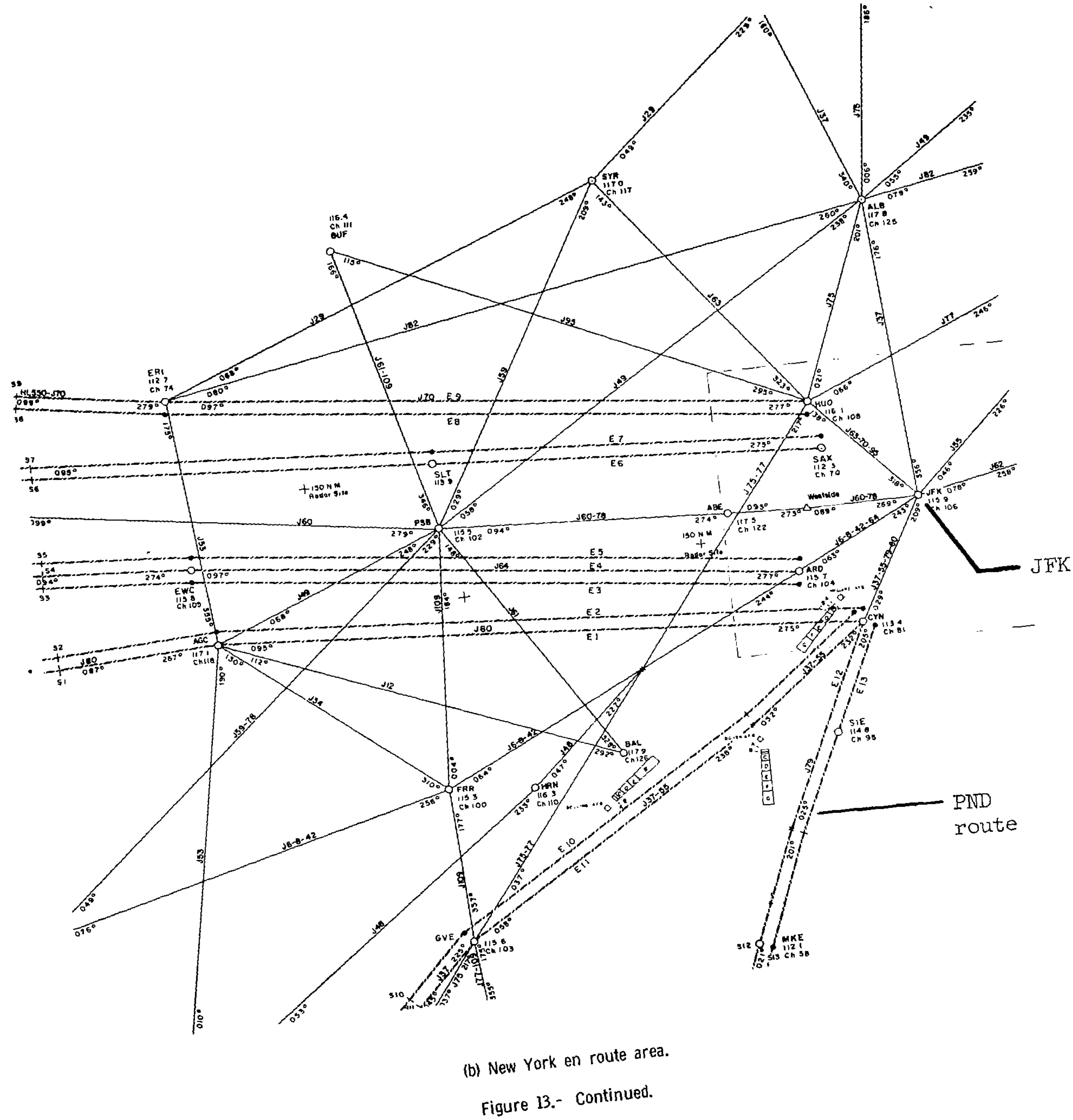
(d) SFO terminal arrival routes.

Figure 12.- Concluded.



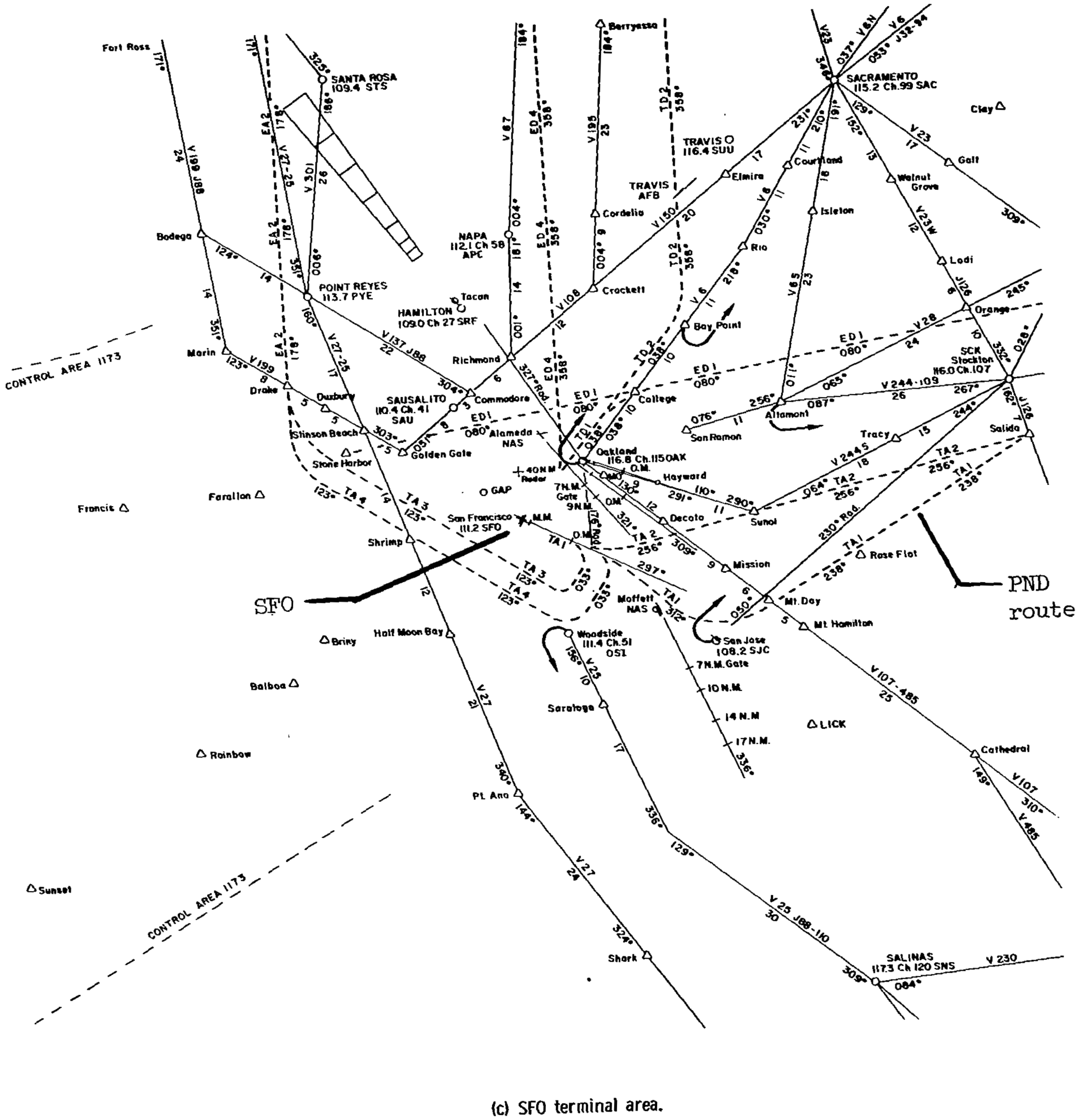
(a) JFK terminal area.

Figure 13.- Terminal and en route PND routes.



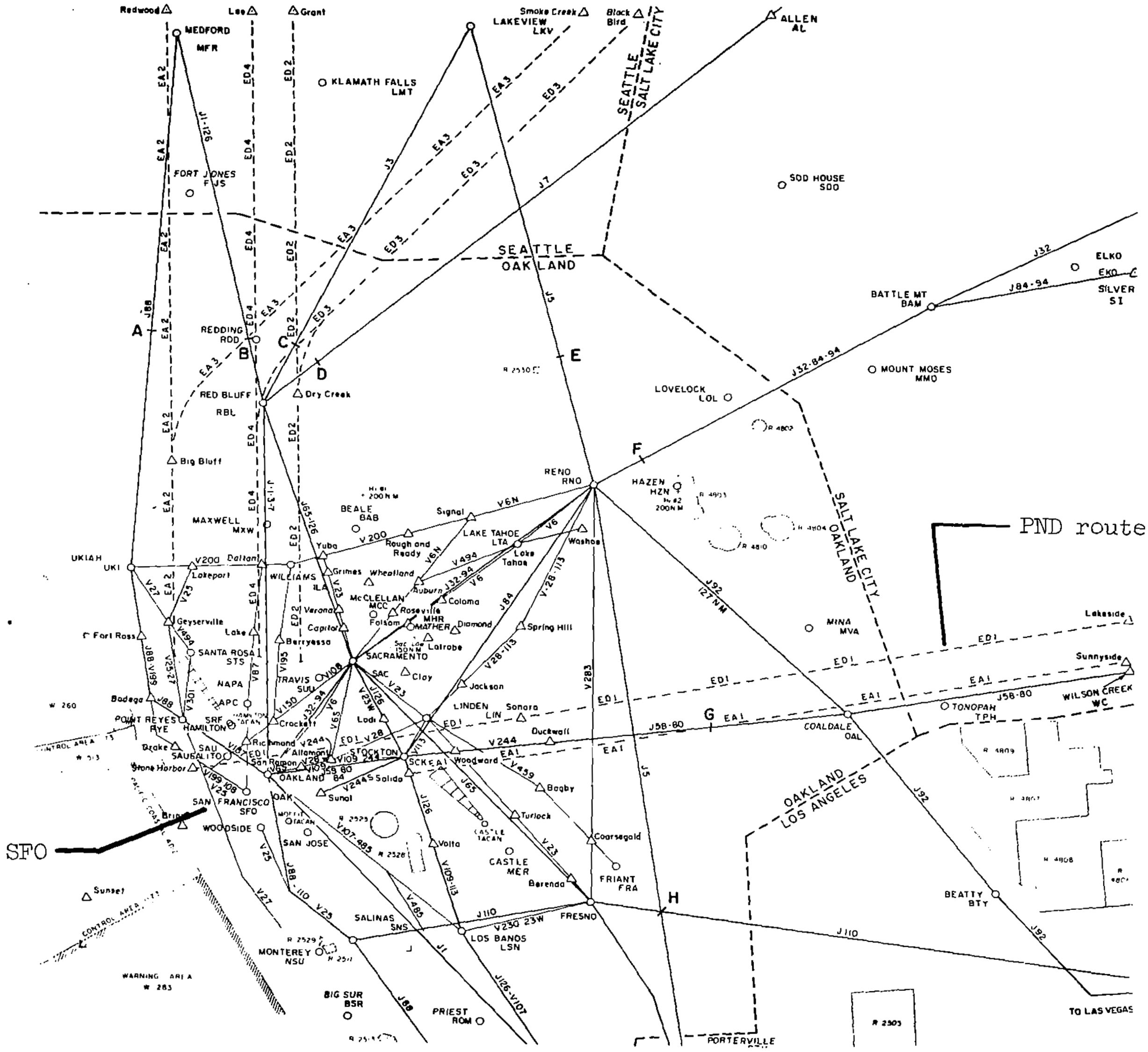
(b) New York en route area.

Figure 13.- Continued.



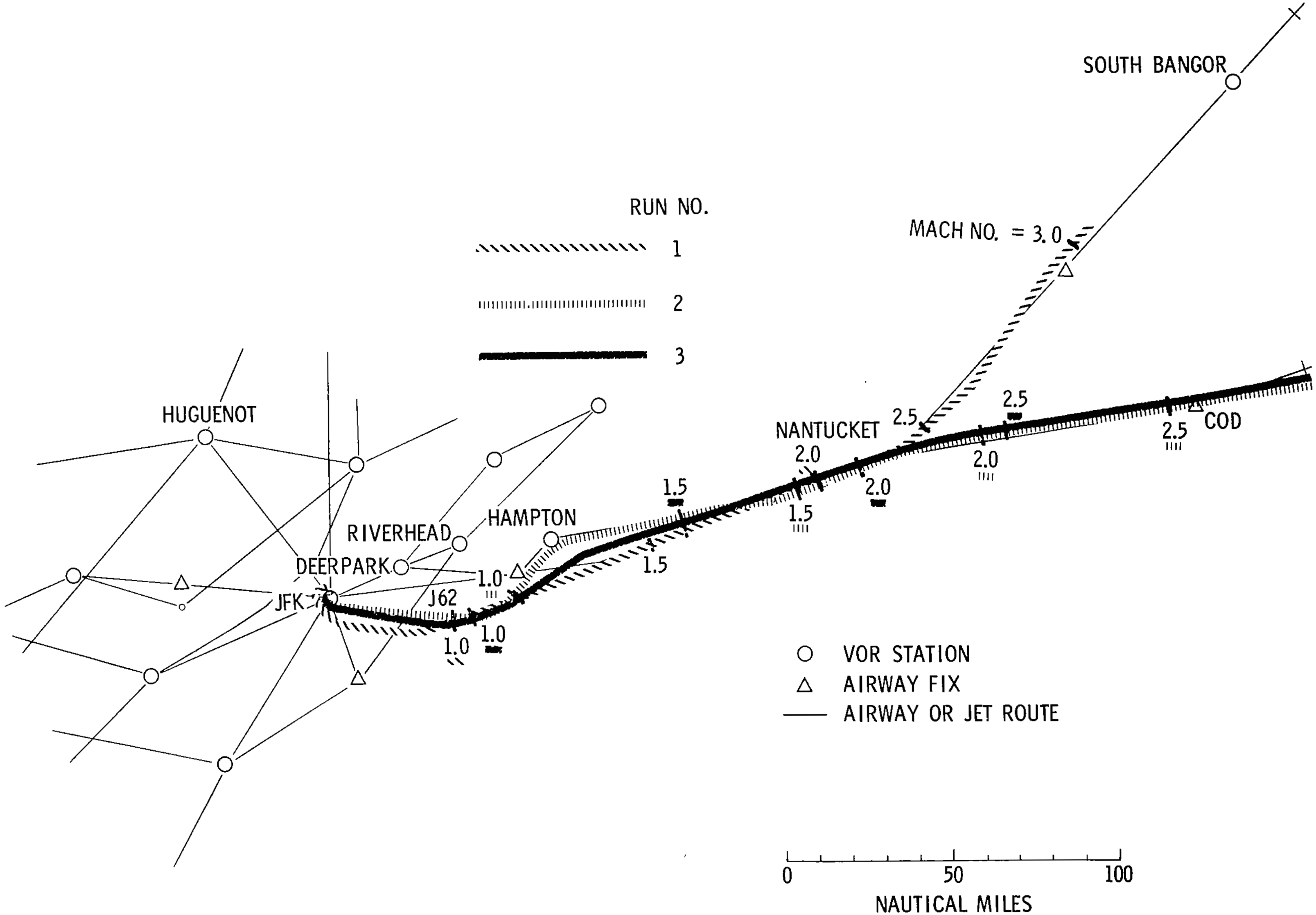
(c) SFO terminal area.

Figure 13.- Continued.



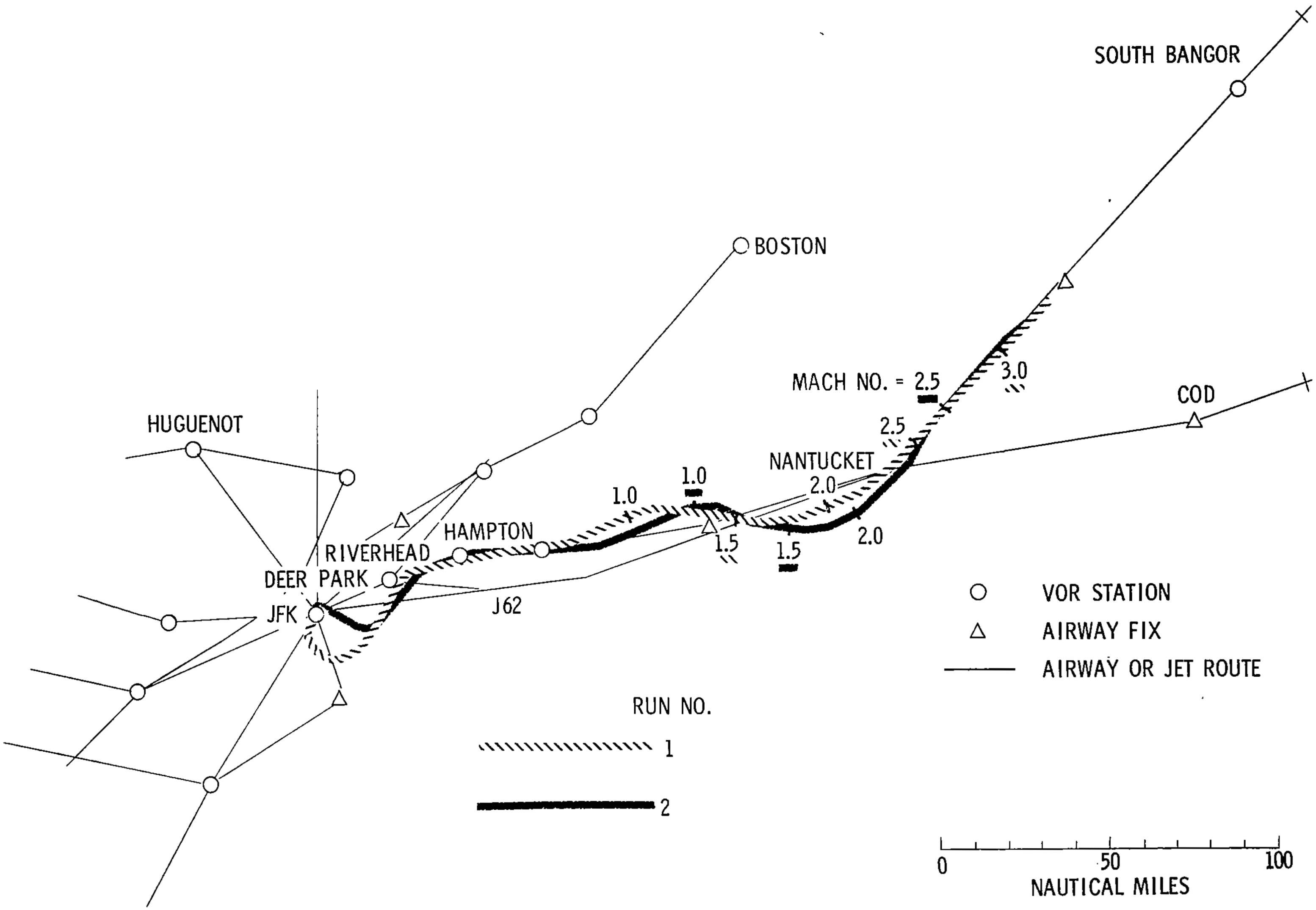
(d) SFO en route area.

Figure 13.- Concluded.



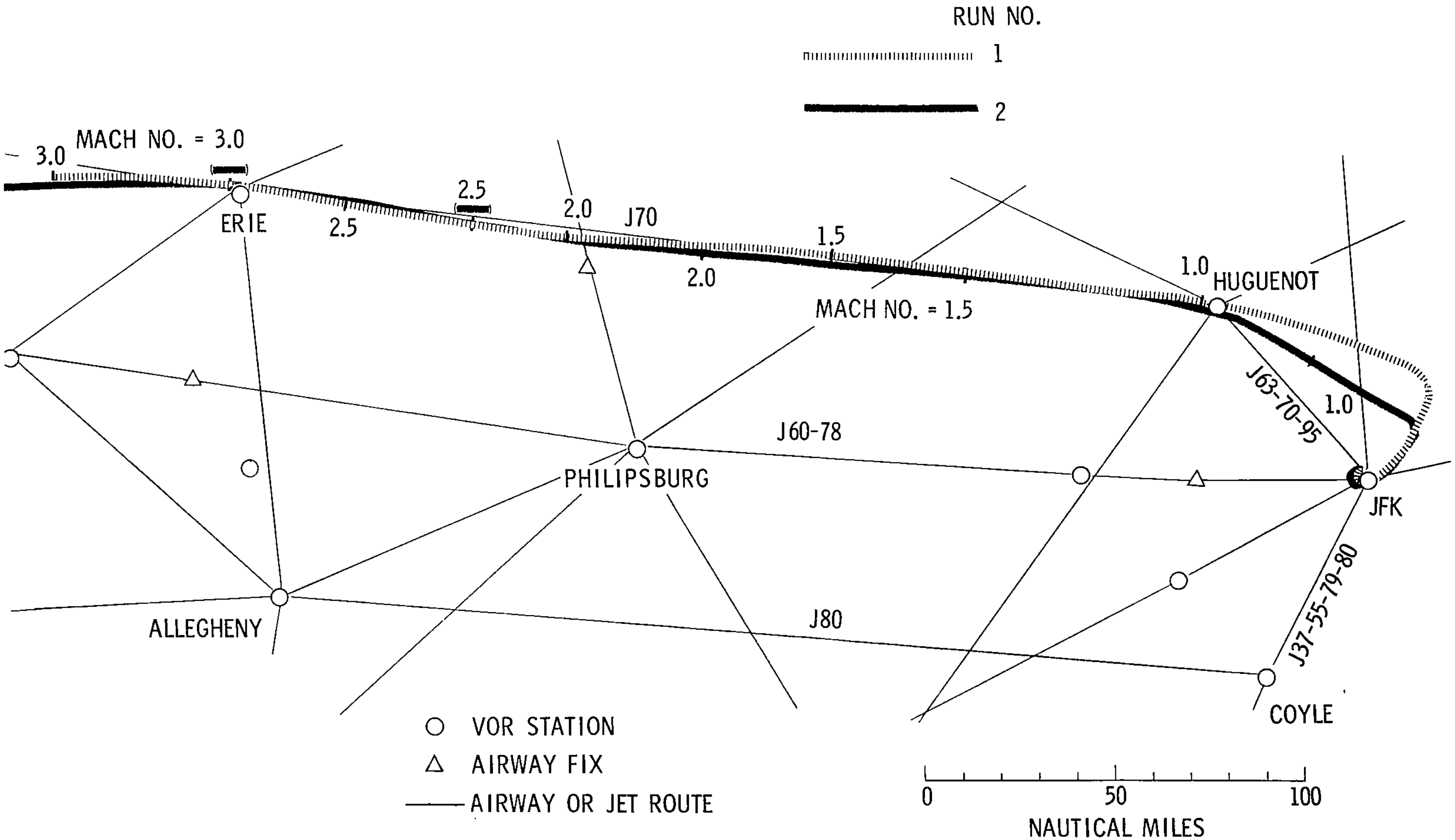
(a) New York oceanic departures.

Figure 14.- Examples of ground tracks for departure and arrival operations of SST in present-day ATC system.



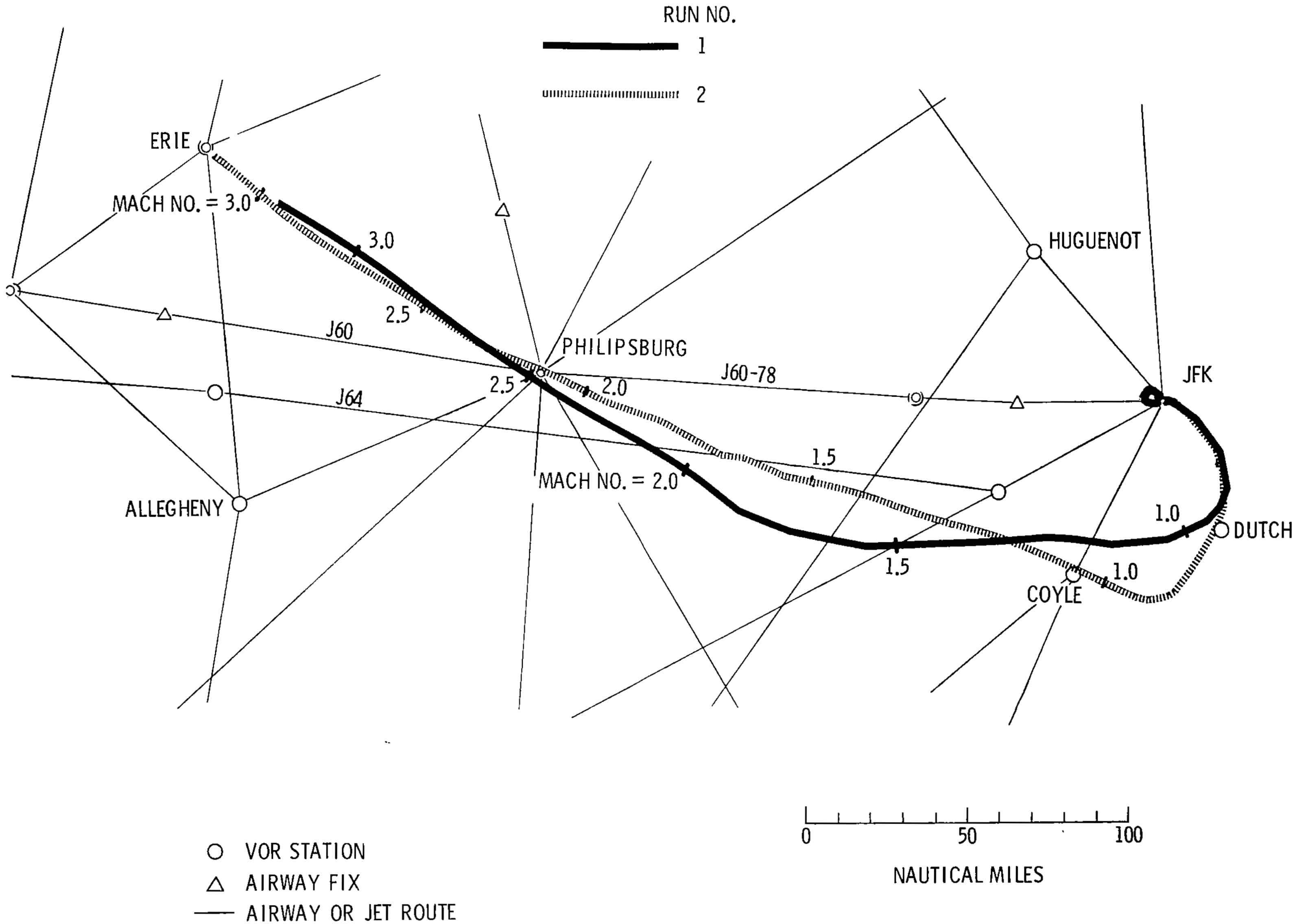
(b) New York oceanic arrivals.

Figure 14.- Continued.



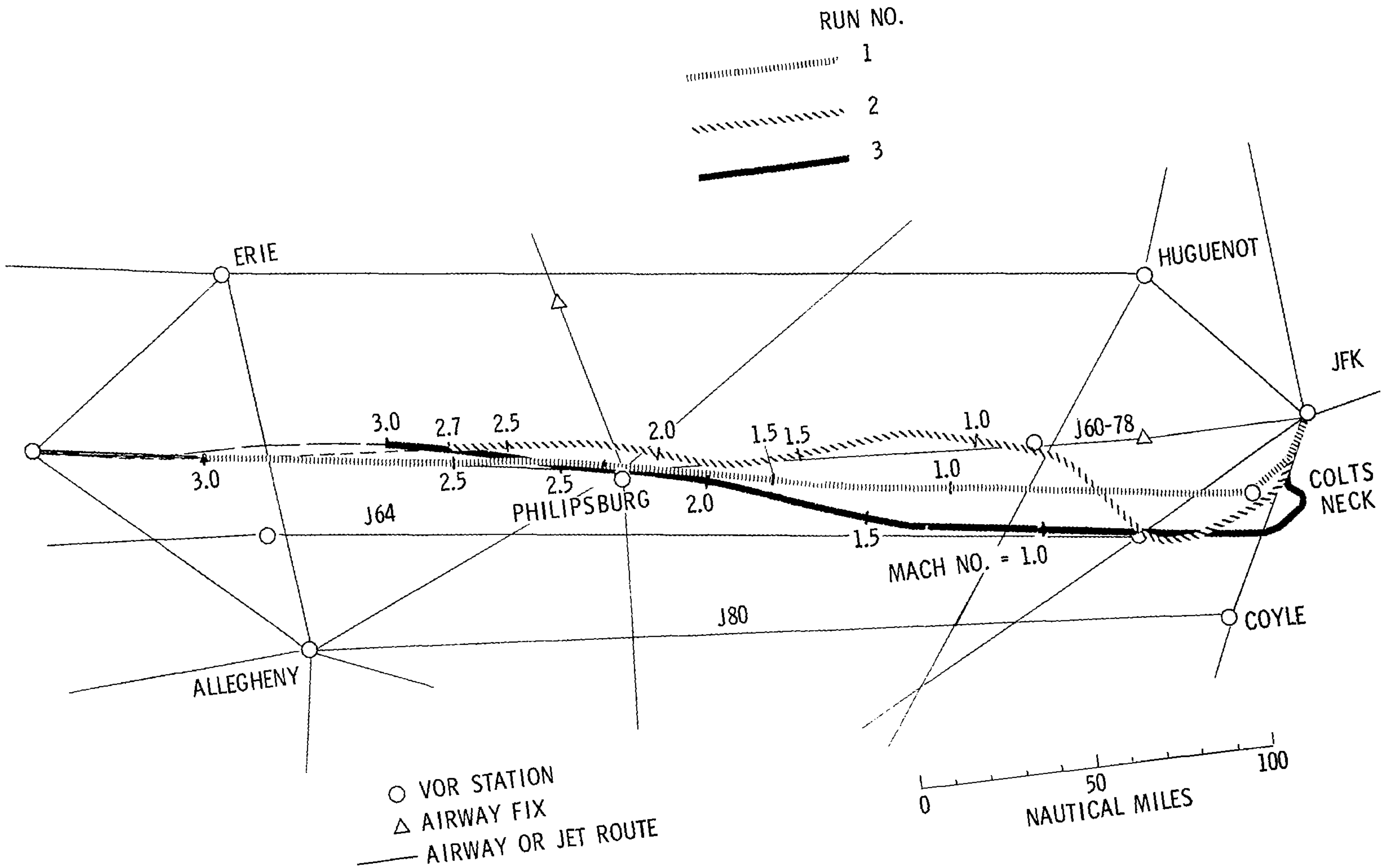
(c) New York domestic departures via Huguenot.

Figure 14.- Continued.



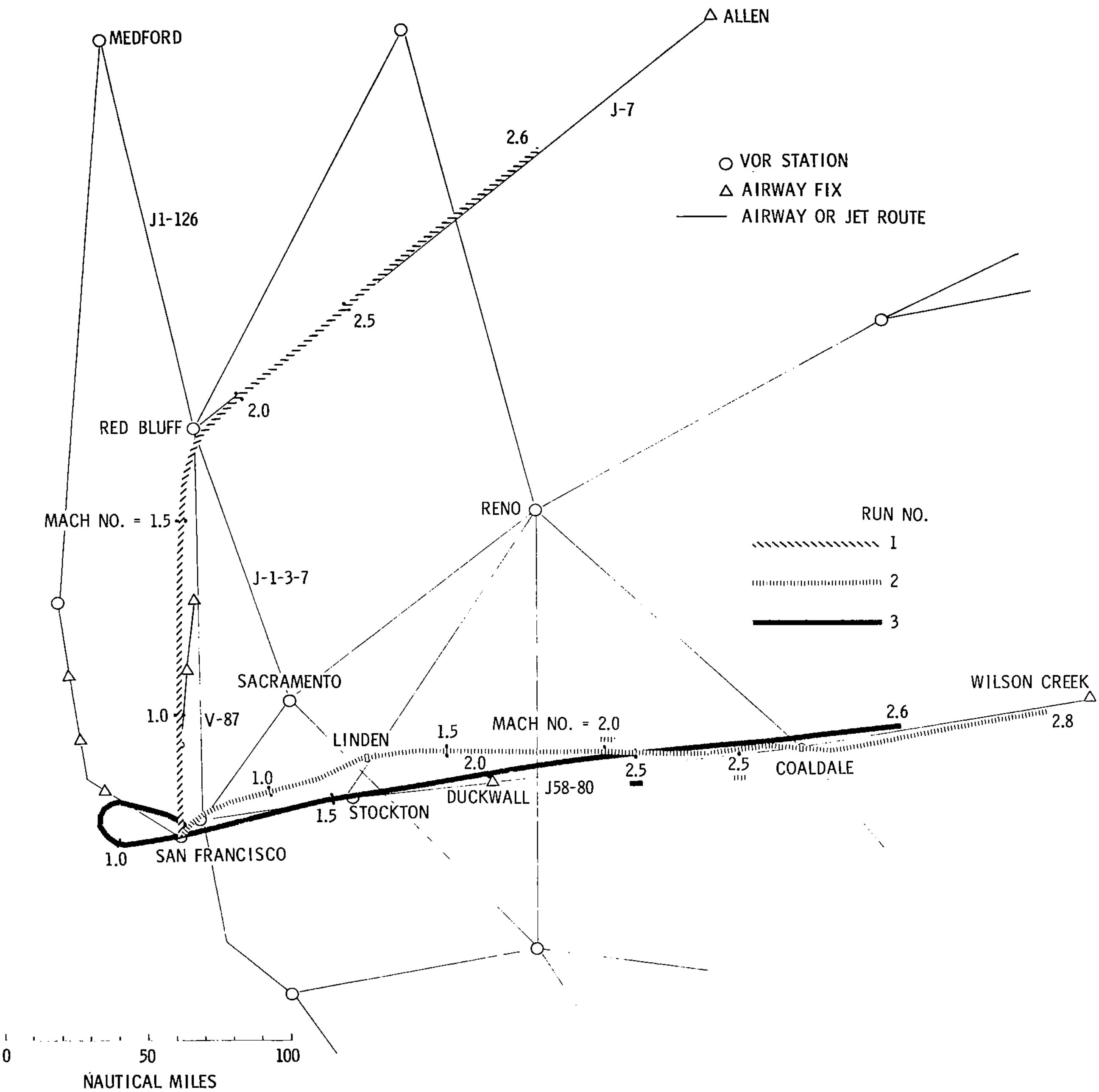
(d) New York domestic departures via Dutch.

Figure 14.- Continued.



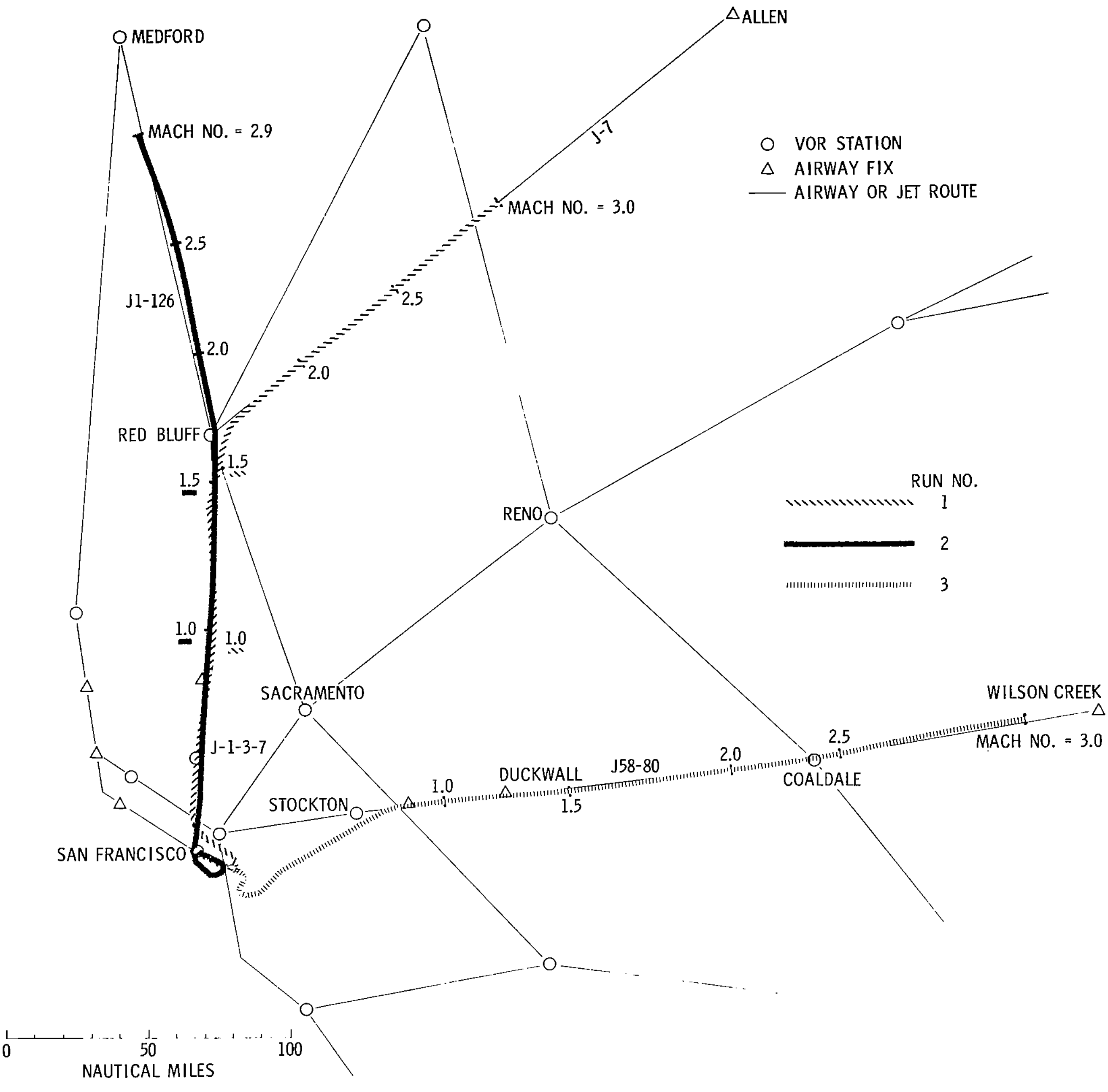
(e) New York domestic arrivals.

Figure 14.- Continued.



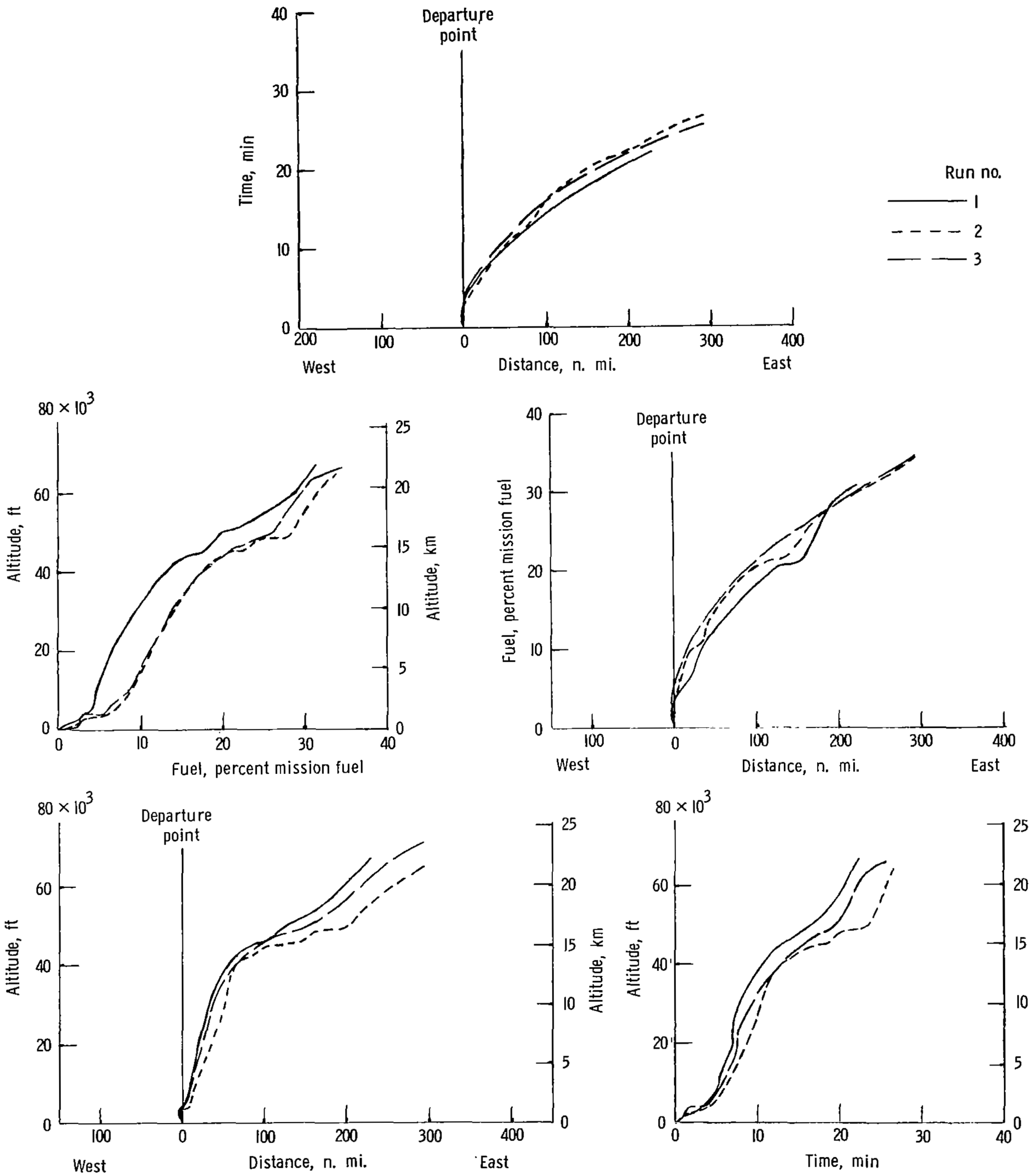
(f) San Francisco domestic departures.

Figure 14.- Continued.



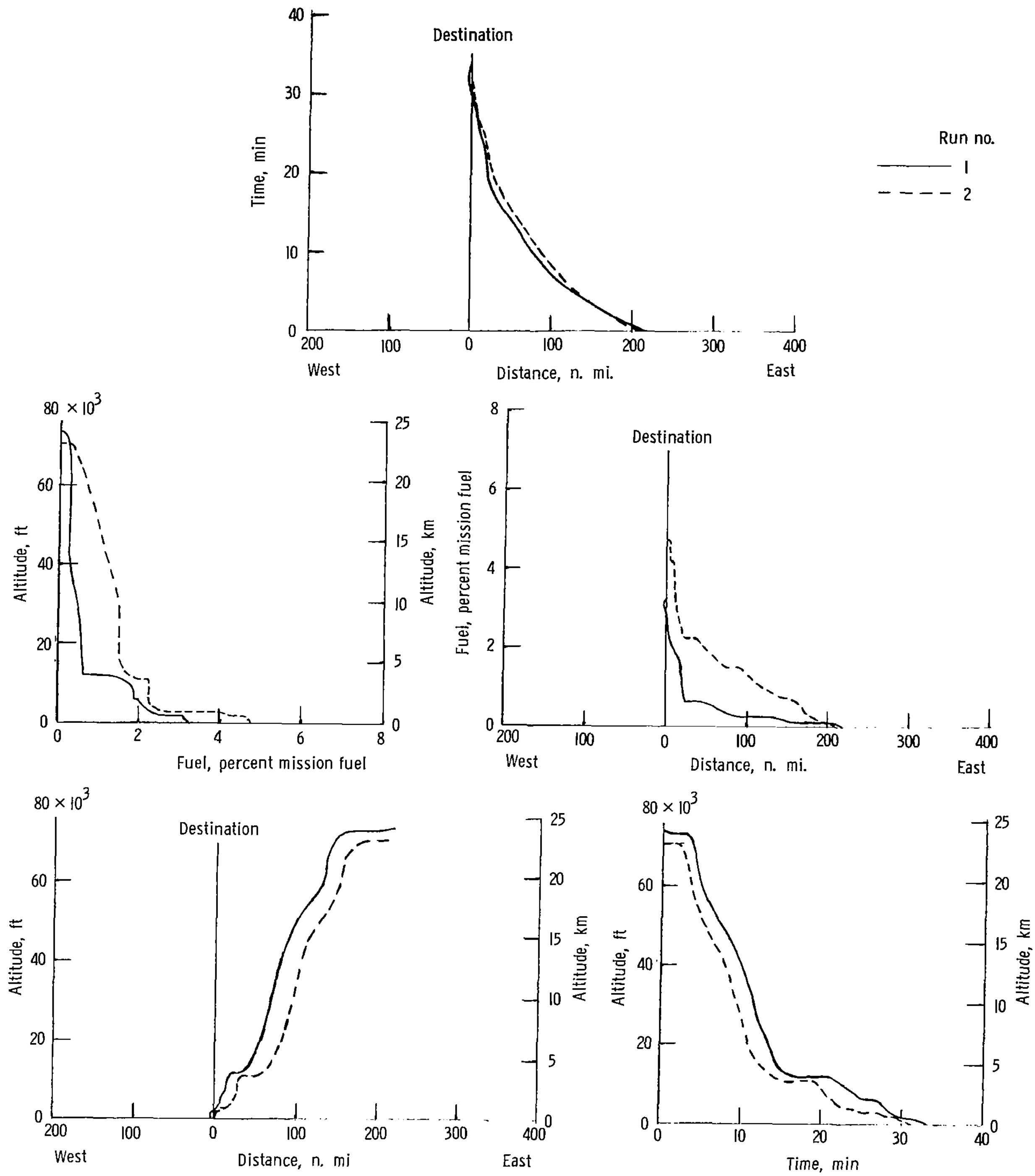
(g) San Francisco domestic arrivals.

Figure 14.- Concluded.



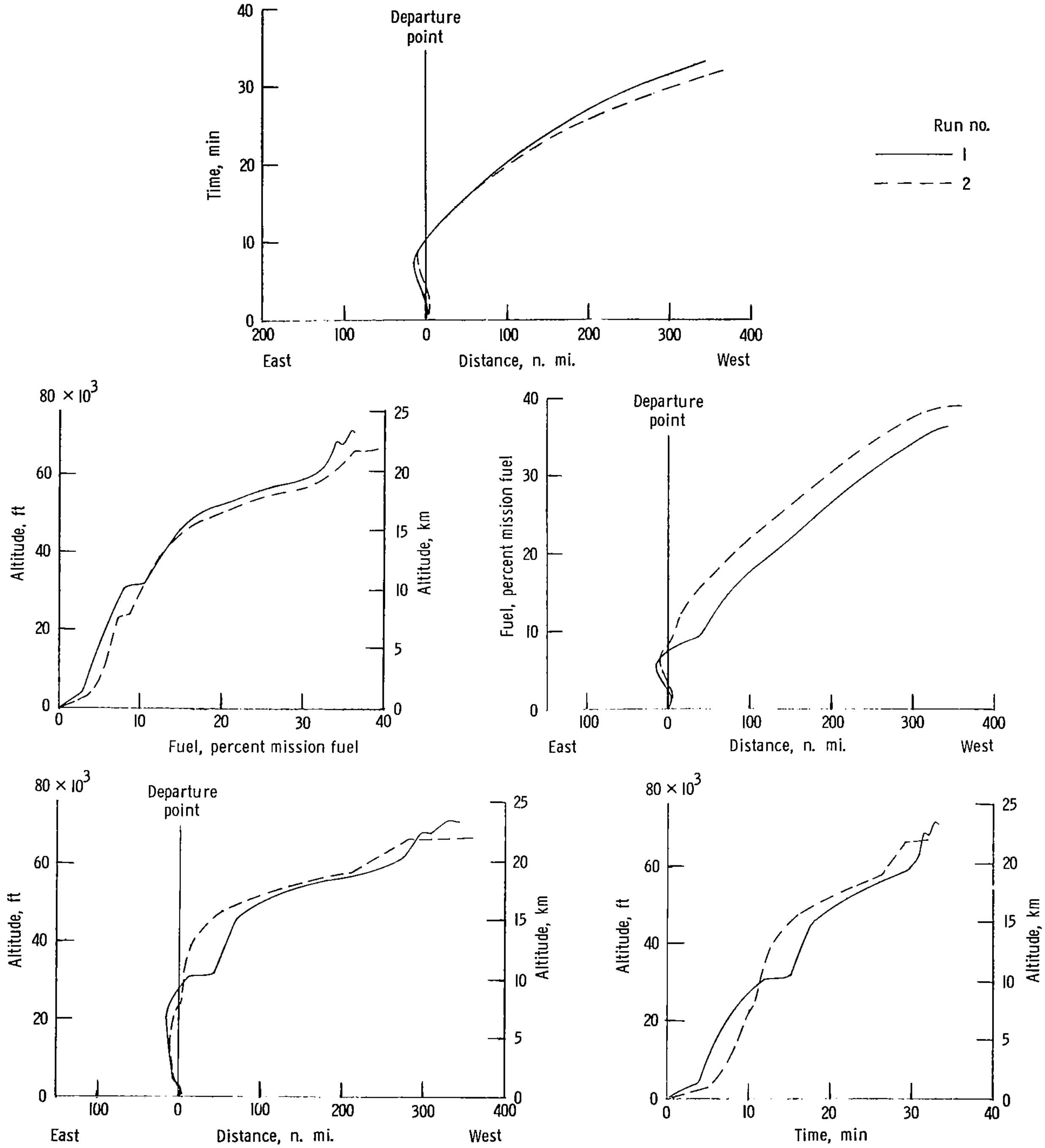
(a) New York oceanic departures.

Figure 15. - Examples of altitude, fuel, time, and distance relationships for departure and arrival operations of SST in present-day ATC system.



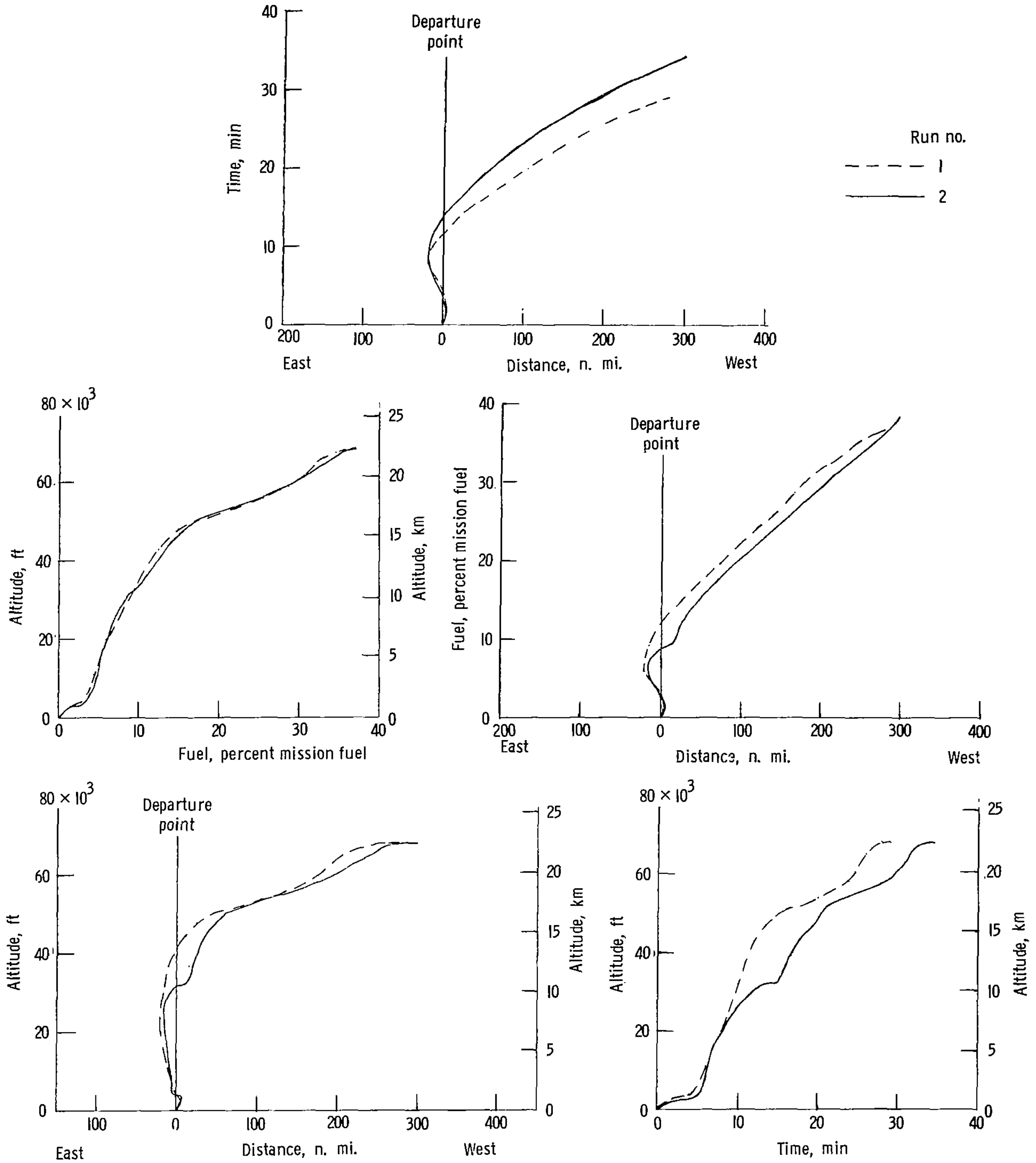
(b) New York oceanic arrivals.

Figure 15. - Continued.



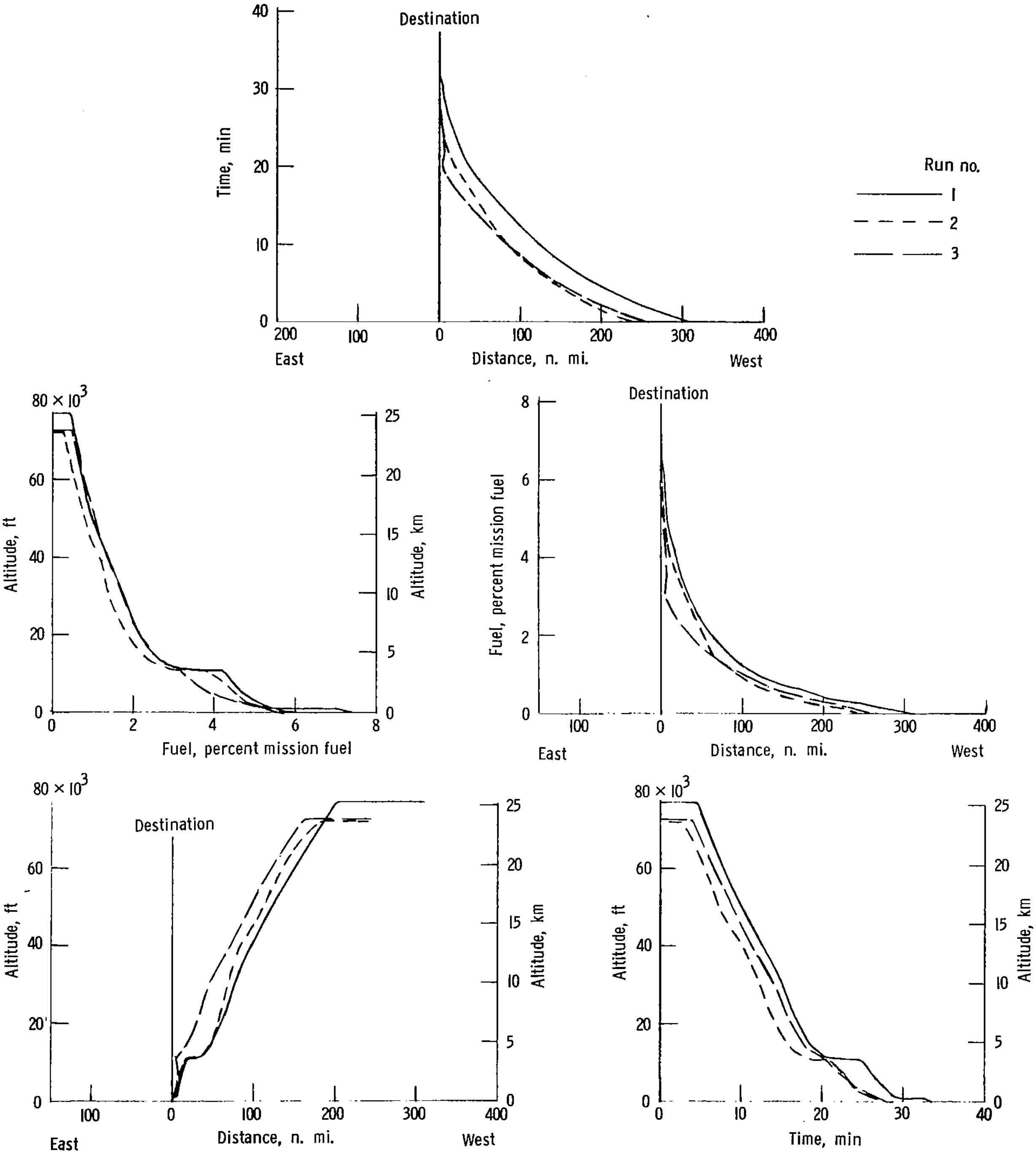
(c) New York domestic departures via Huguenot.

Figure 15. - Continued.



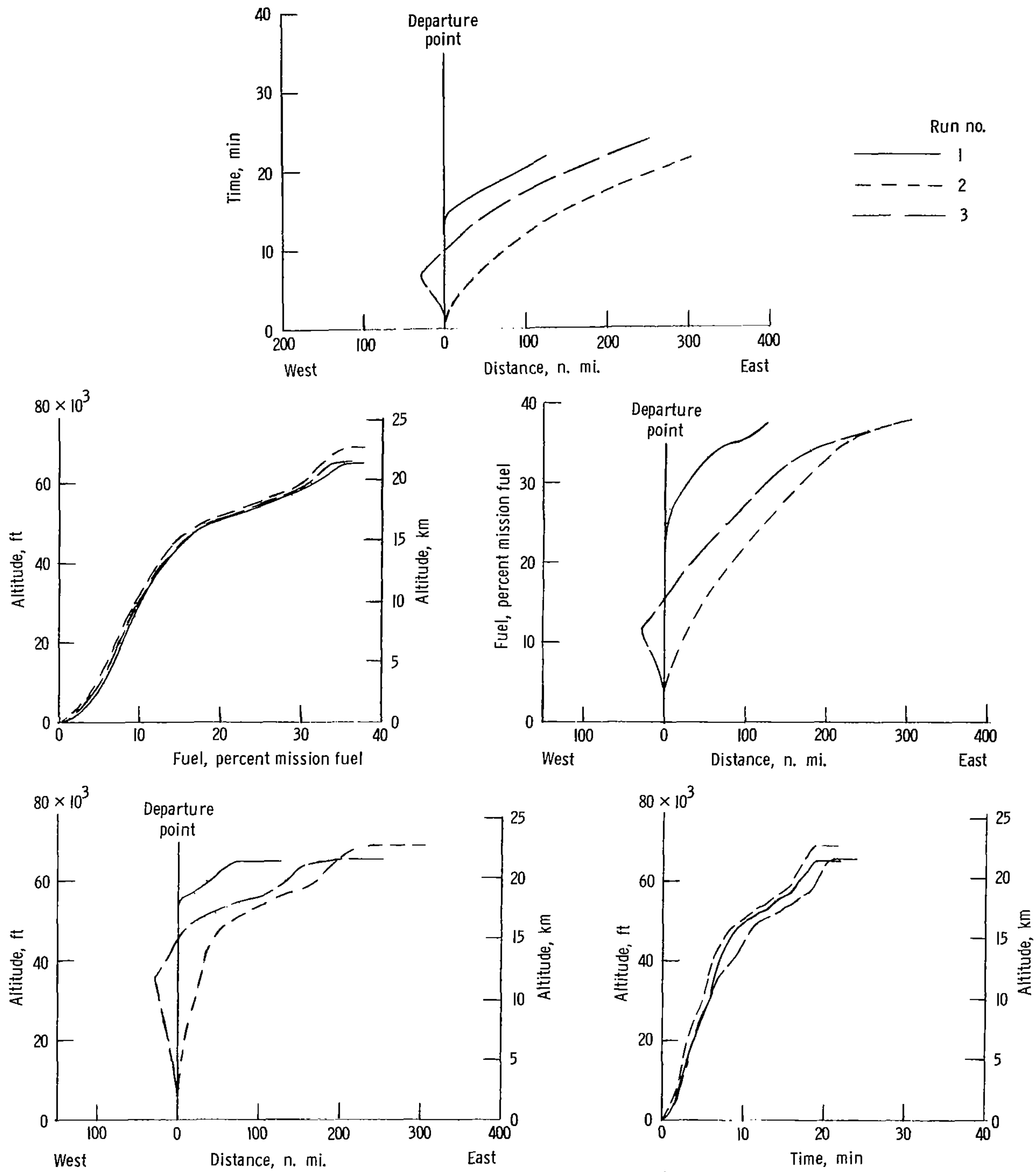
(d) New York domestic departures via Dutch.

Figure 15. - Continued.



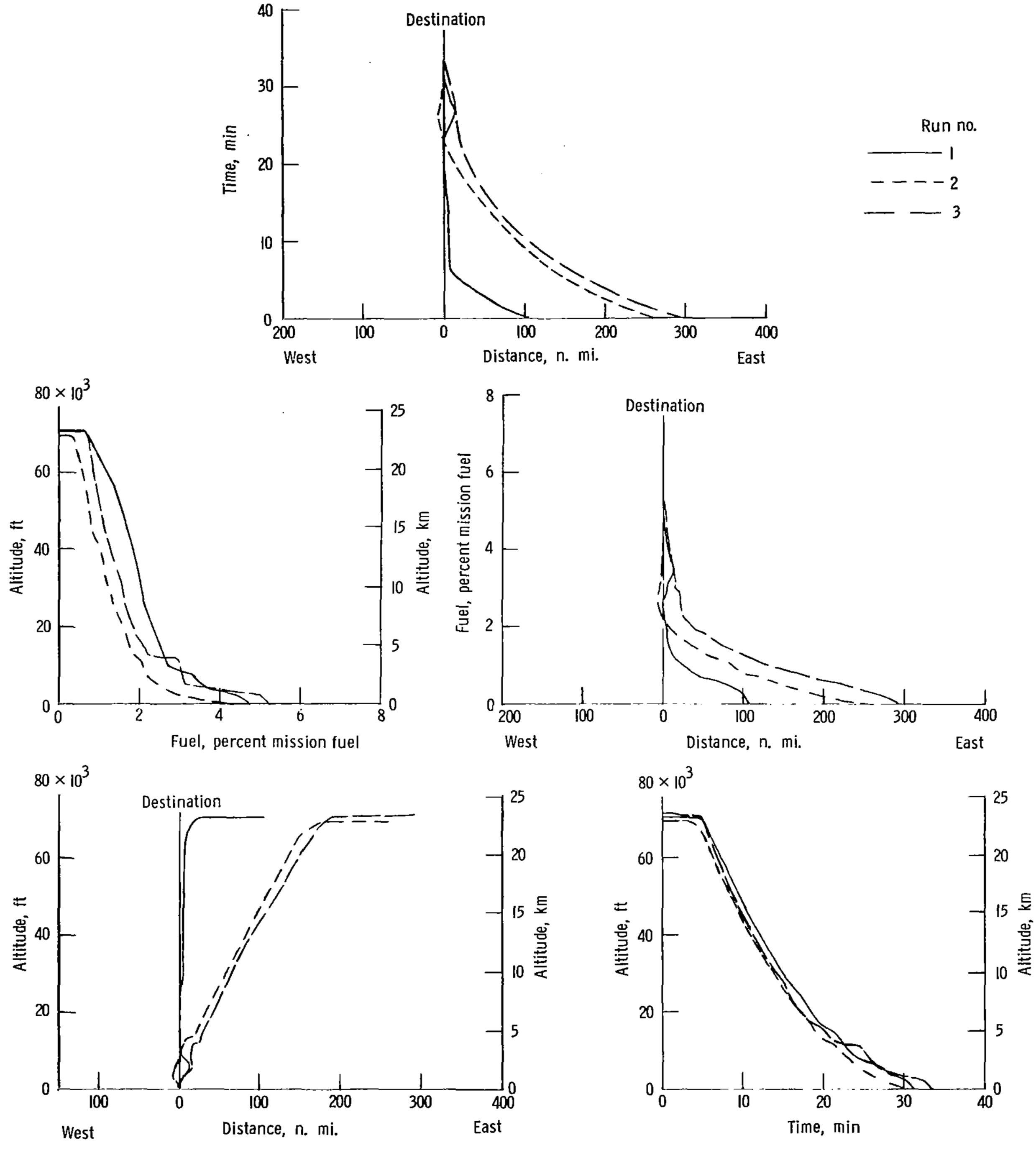
(e) New York domestic arrivals.

Figure 15. - Continued.



(f) San Francisco domestic departures.

Figure 15. - Continued.



(g) San Francisco domestic arrivals.

Figure 15.- Concluded.

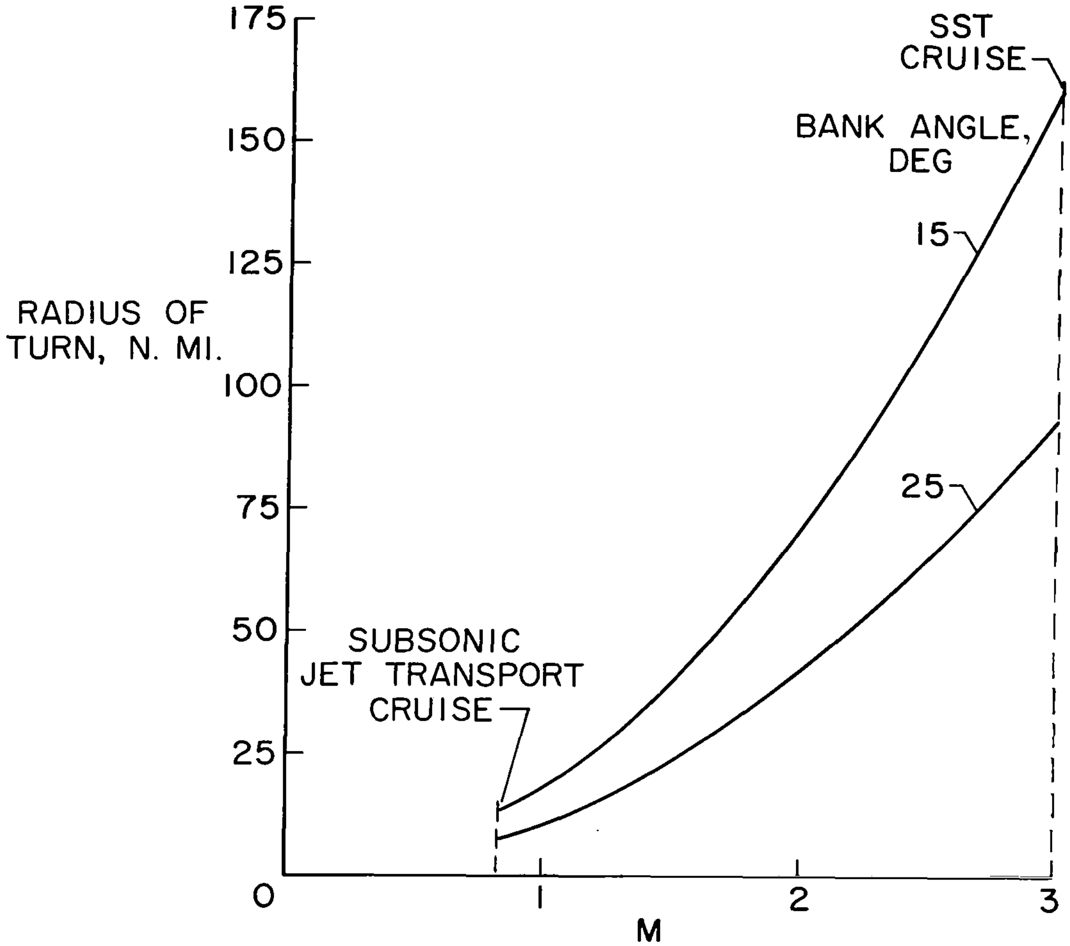


Figure 16.- Variation of radius of turn with Mach number for two bank angles. For flight under standard temperature conditions above the tropopause.

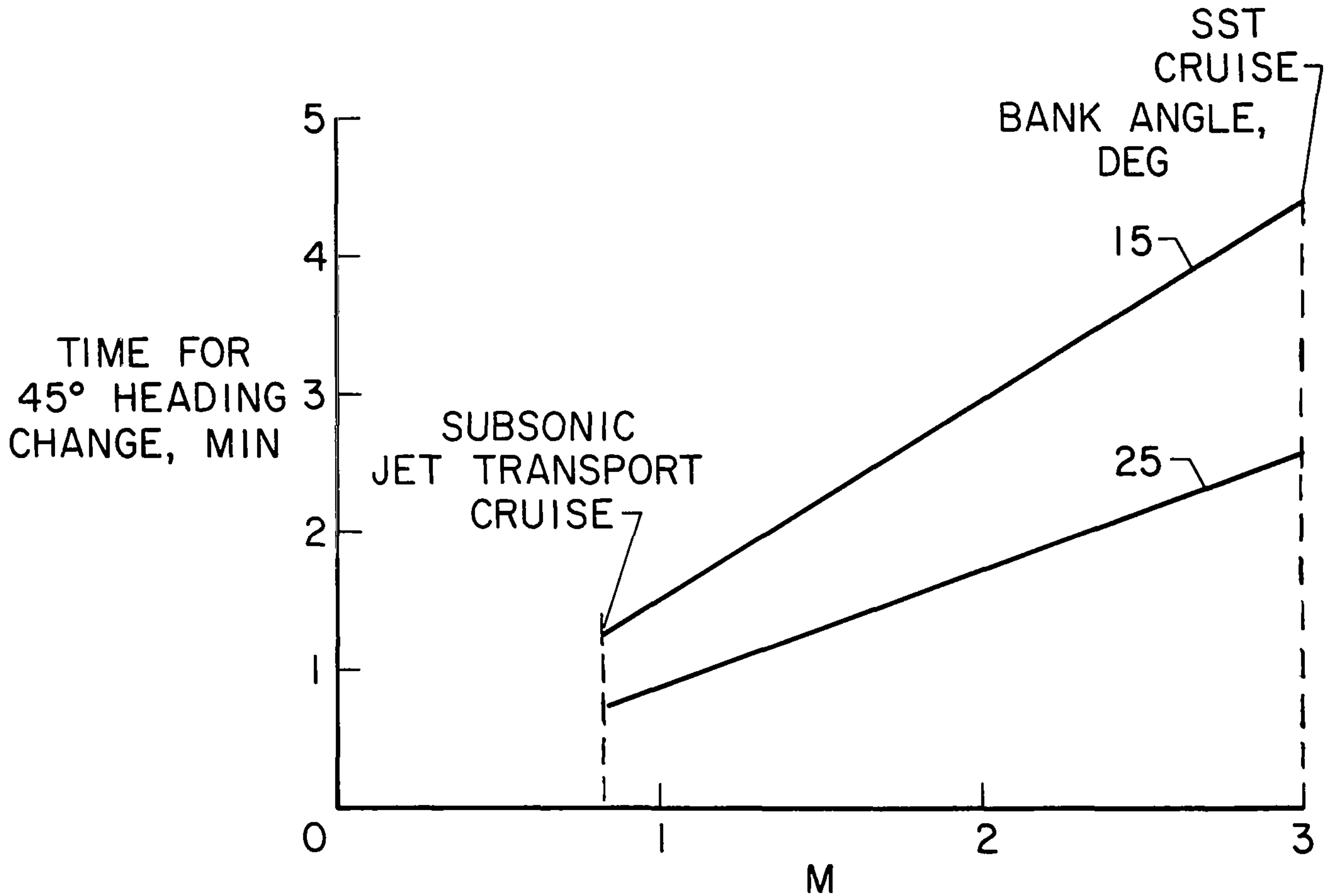


Figure 17.- Variation of time required for heading change of 45° with Mach number for two bank angles. For flight under standard temperature conditions above the tropopause.

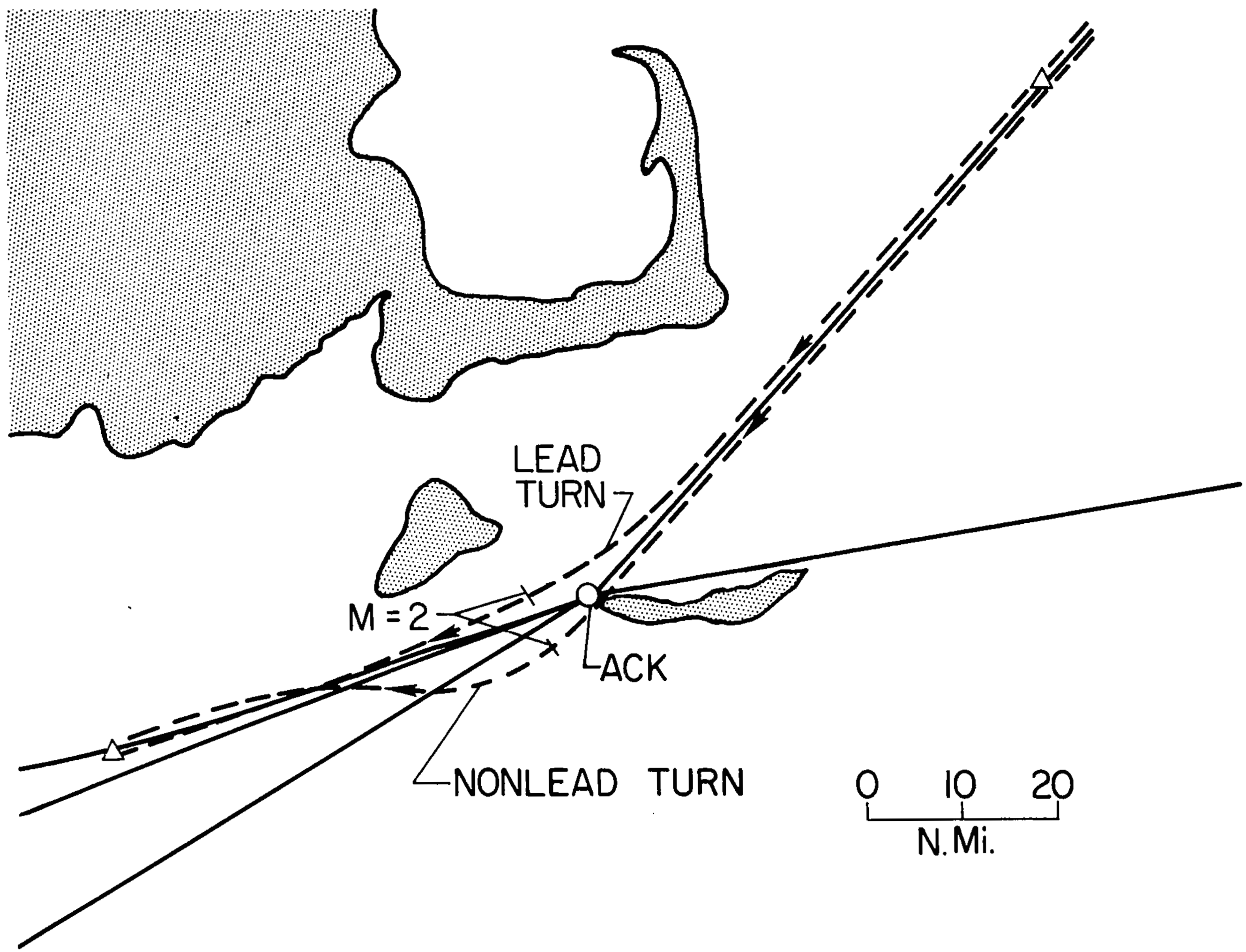


Figure 18.- Examples of ground tracks for supersonic turns at a VORTAC station for lead and nonlead turns.

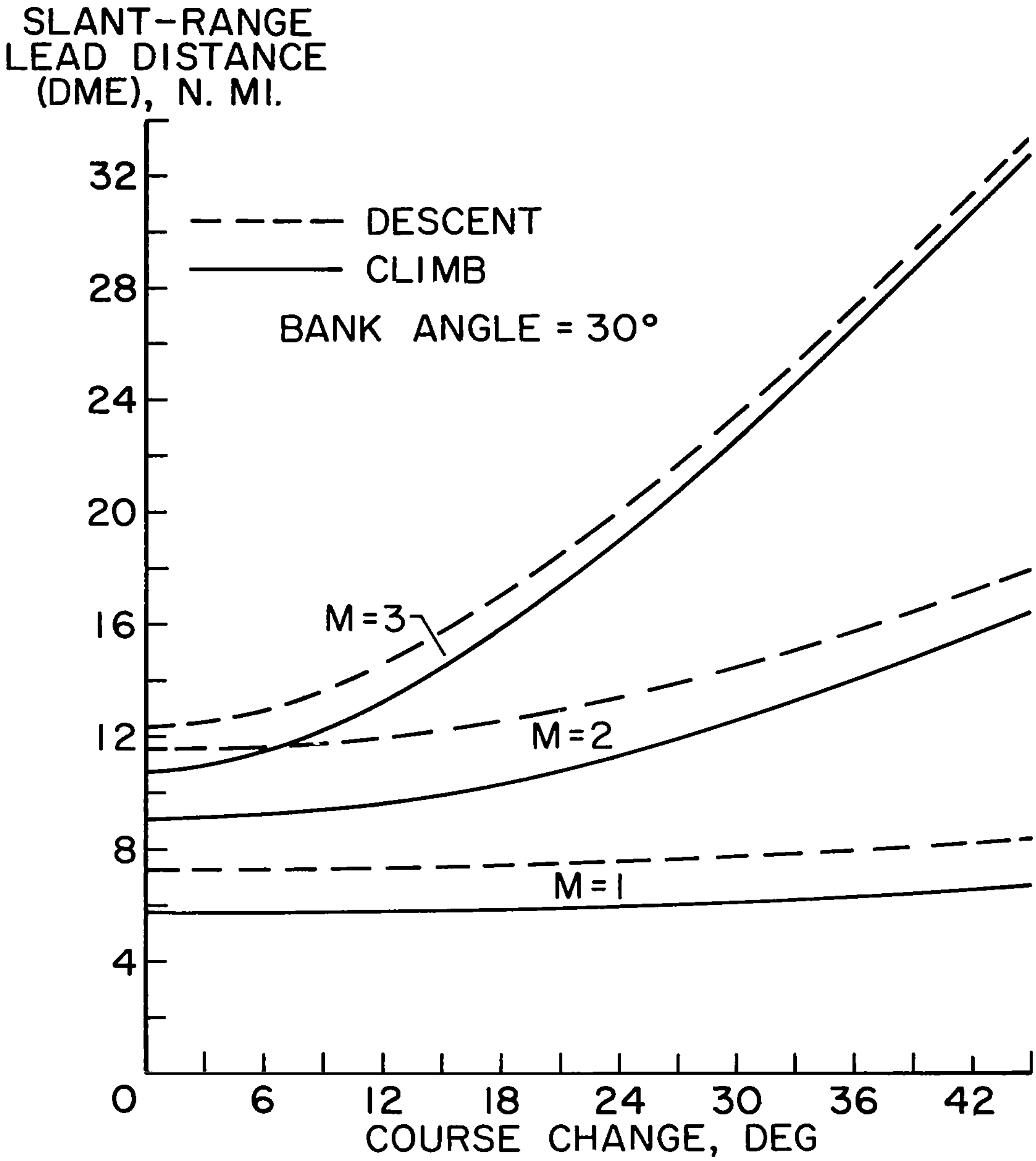


Figure 19.- Slant-range lead distance required for lead turns for various changes in course. For flight along standard profiles (fig. 10) above the tropopause under standard temperature and no-wind conditions.

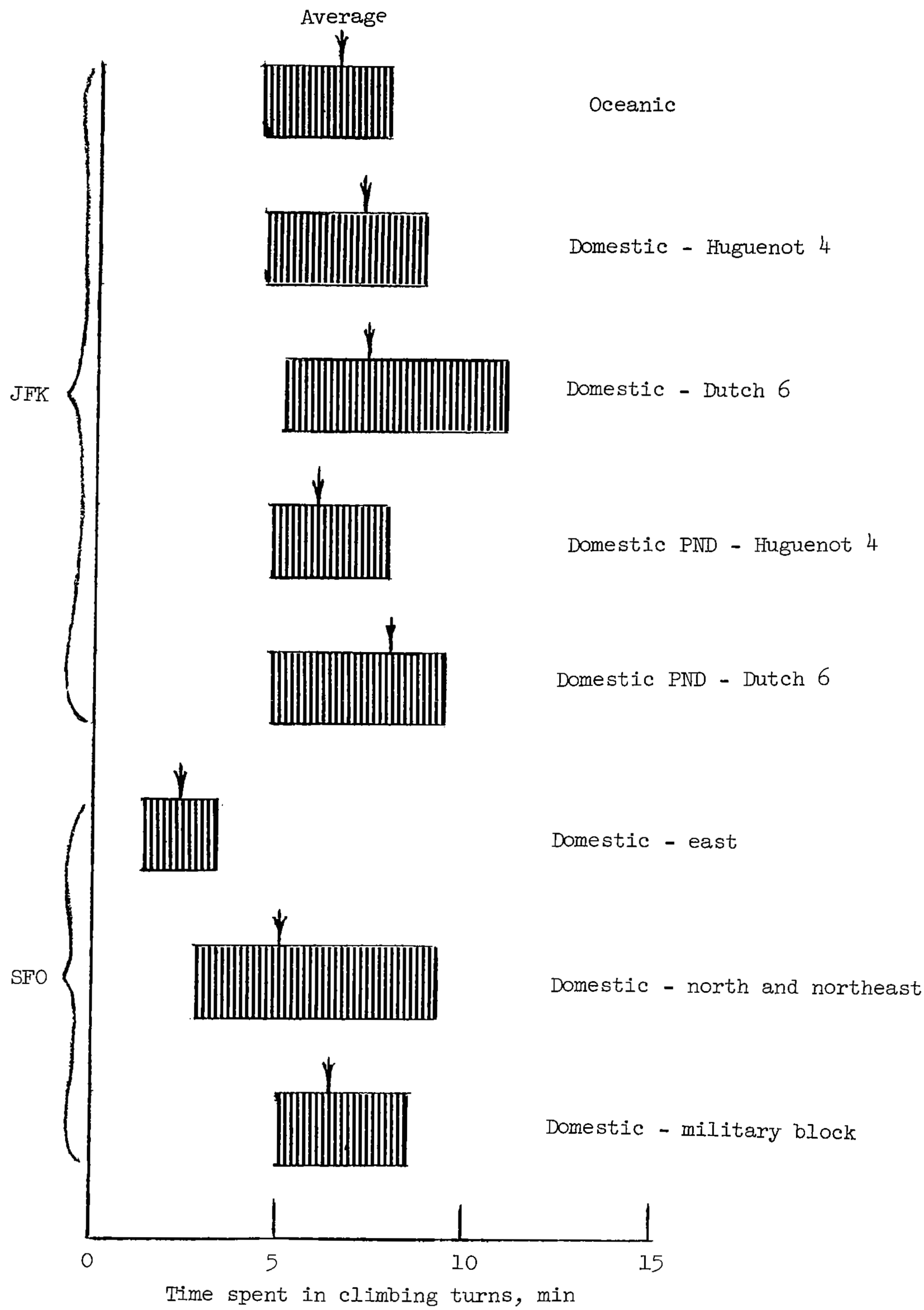


Figure 20.- Time spent in climbing turns. JFK and SFO departure operations.

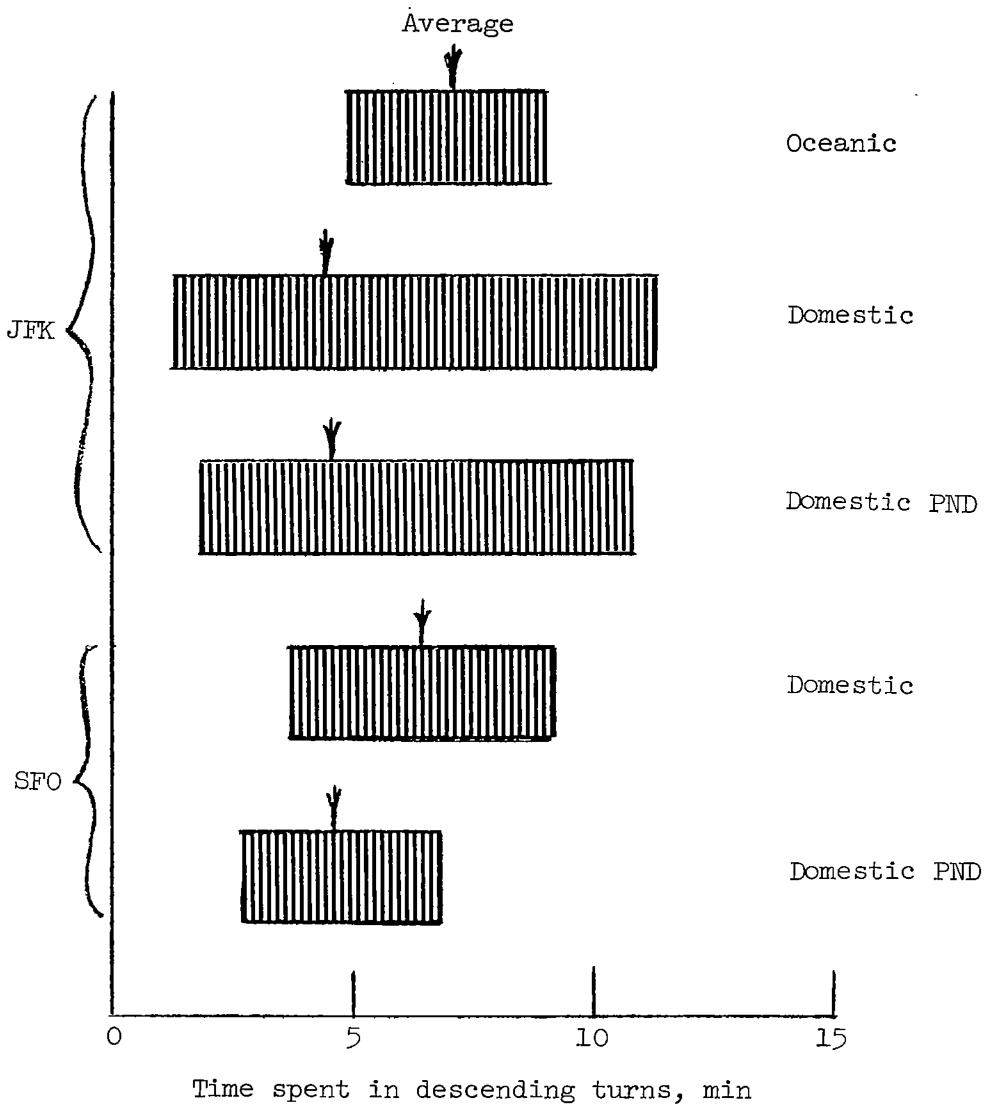


Figure 21.- Time spent in descending turns. JFK and SFO arrival operations.

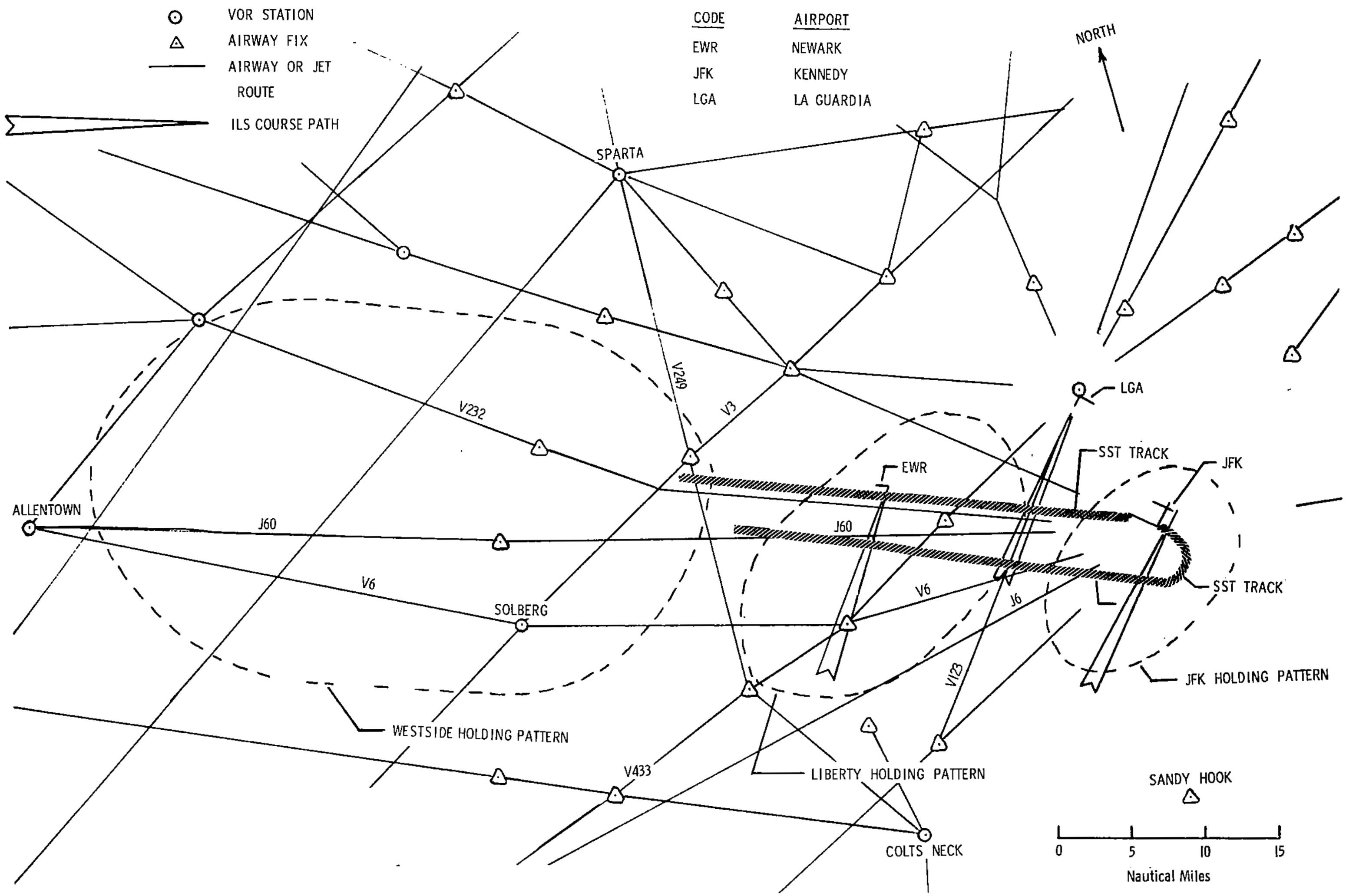
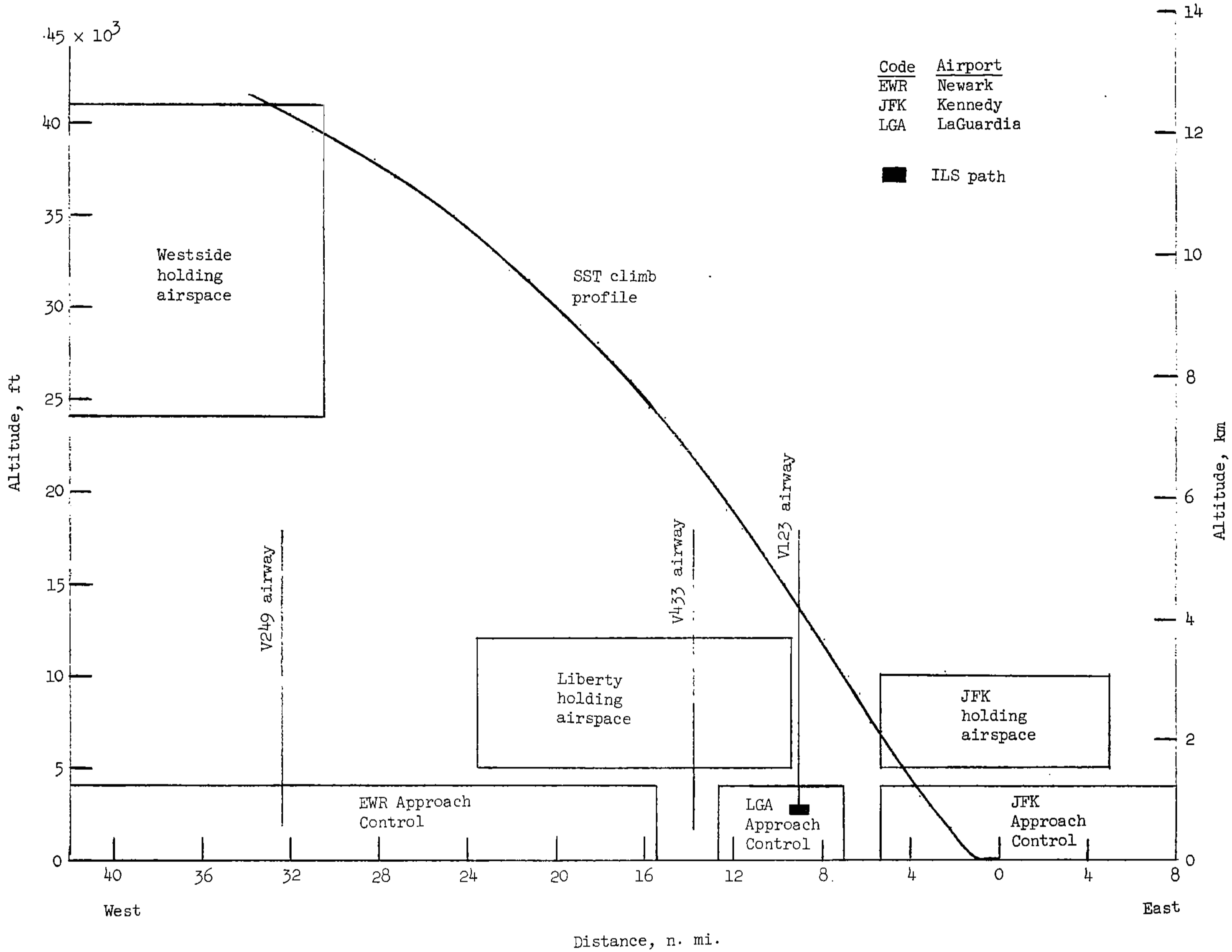
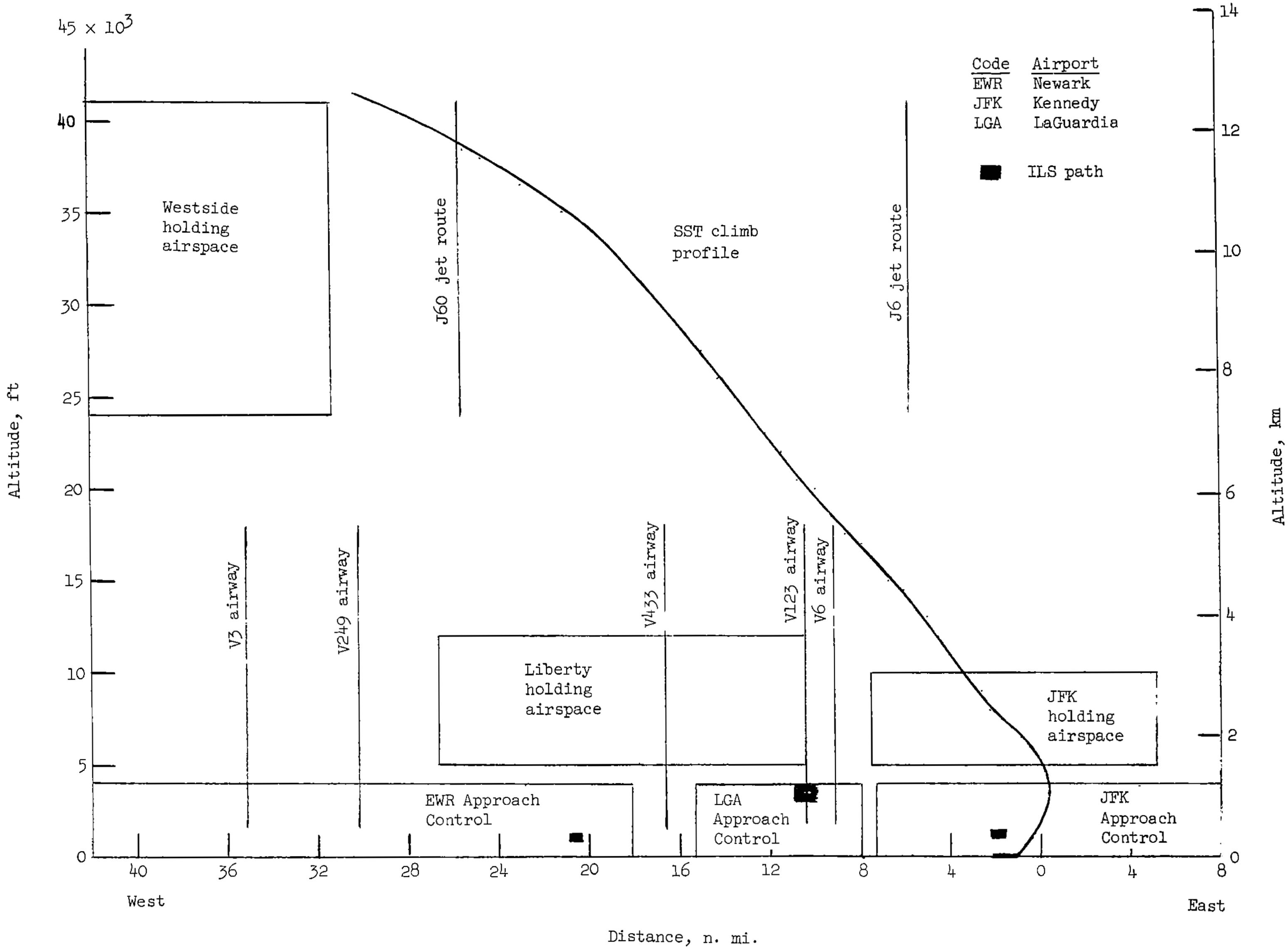


Figure 22.- Ground tracks for domestic-departure climb-corridor operations from JFK.



(a) Take-off from runway 31L.

Figure 23.- Altitude-distance profile for domestic-departure climb-corridor operations from JFK. SST configuration B.



(b) Take-off from runway 13R.

Figure 23.- Concluded.

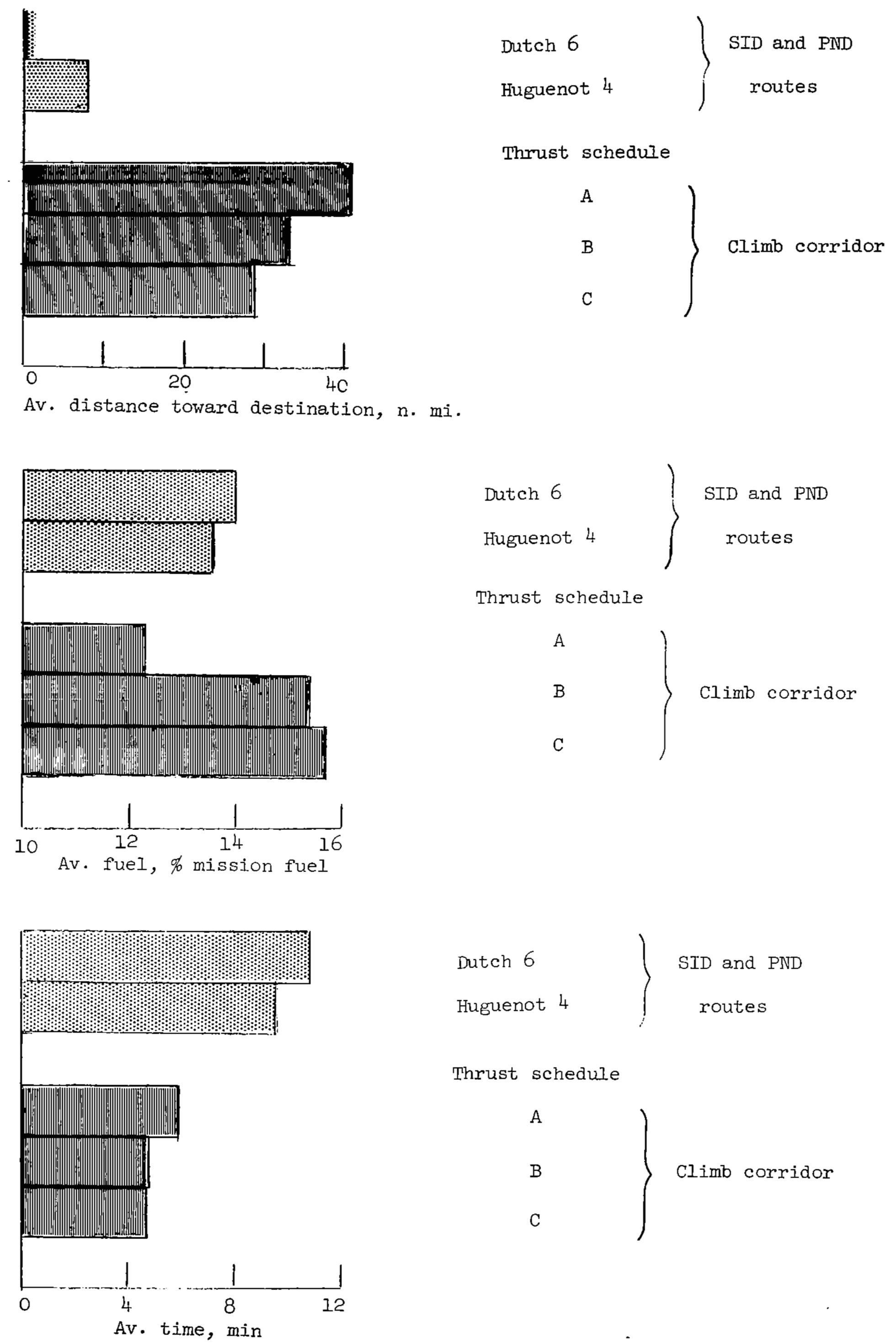
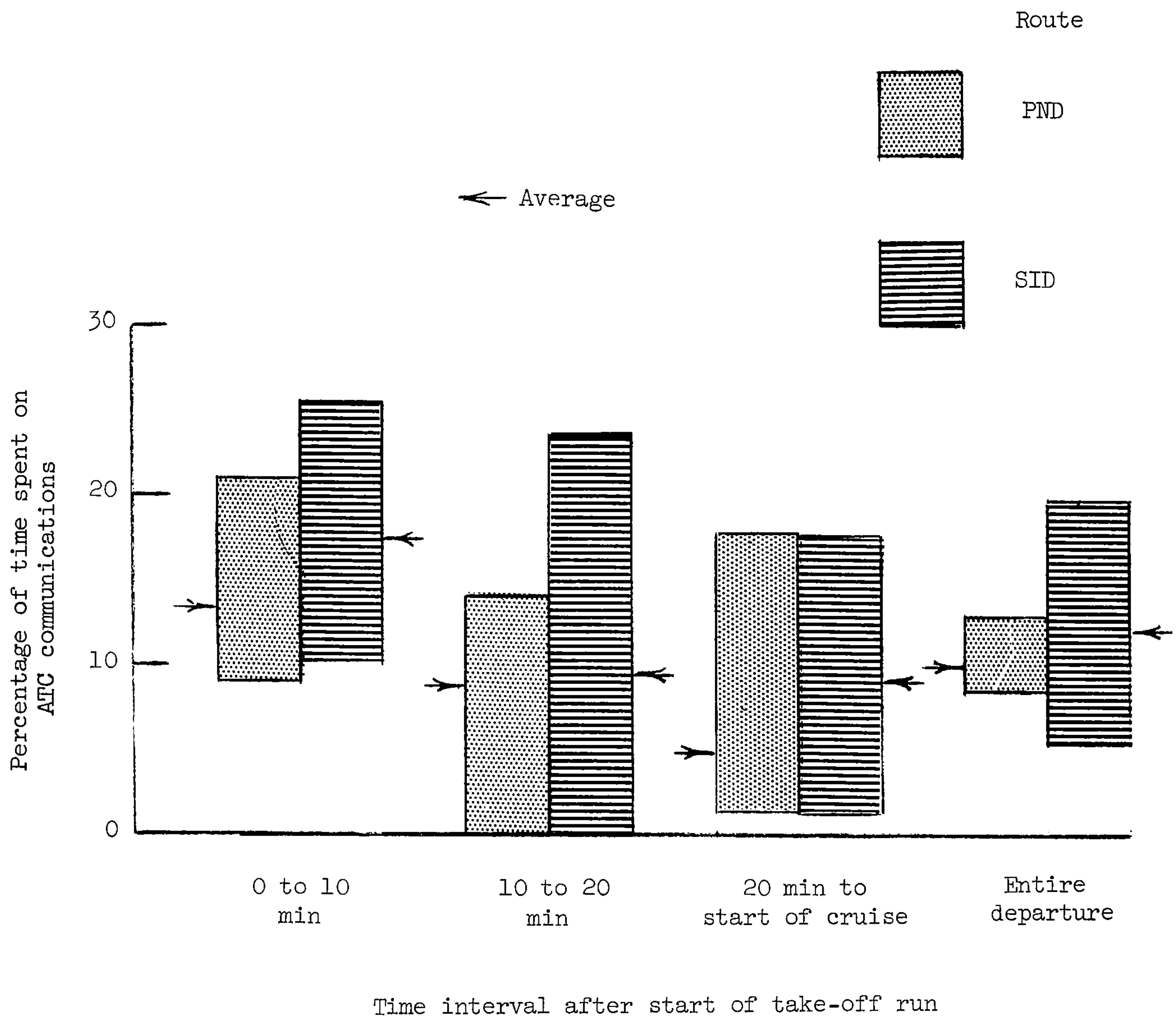
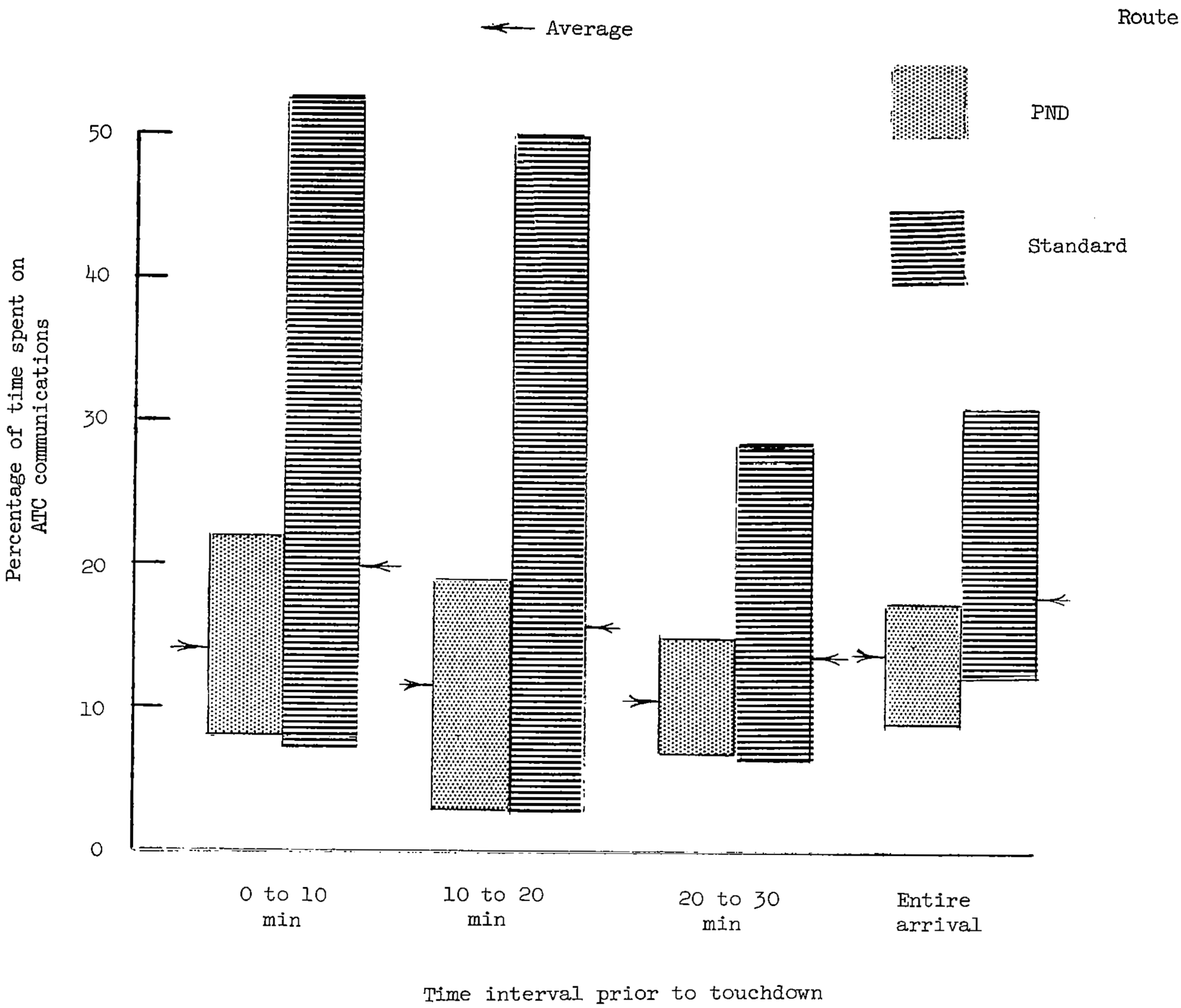


Figure 24.- Average time, fuel, and distance in climbing to FL 400 for SID and PND routes and climb-corridor operations.



(a) Departures.

Figure 25.- Percentage of time spent on ATC communications for SID and PND domestic operations in New York area.



(b) Arrivals.

Figure 25.- Concluded.

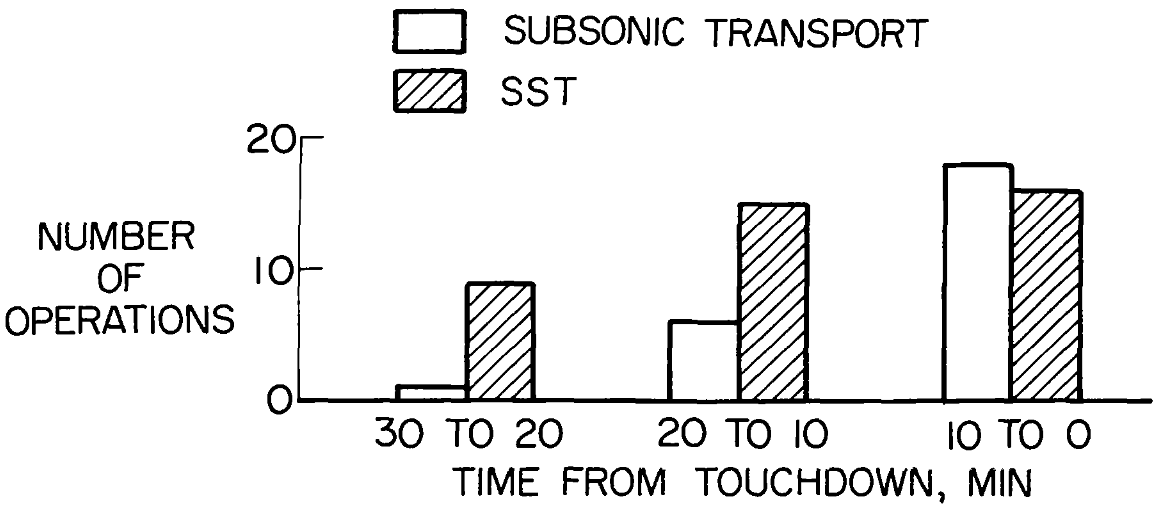
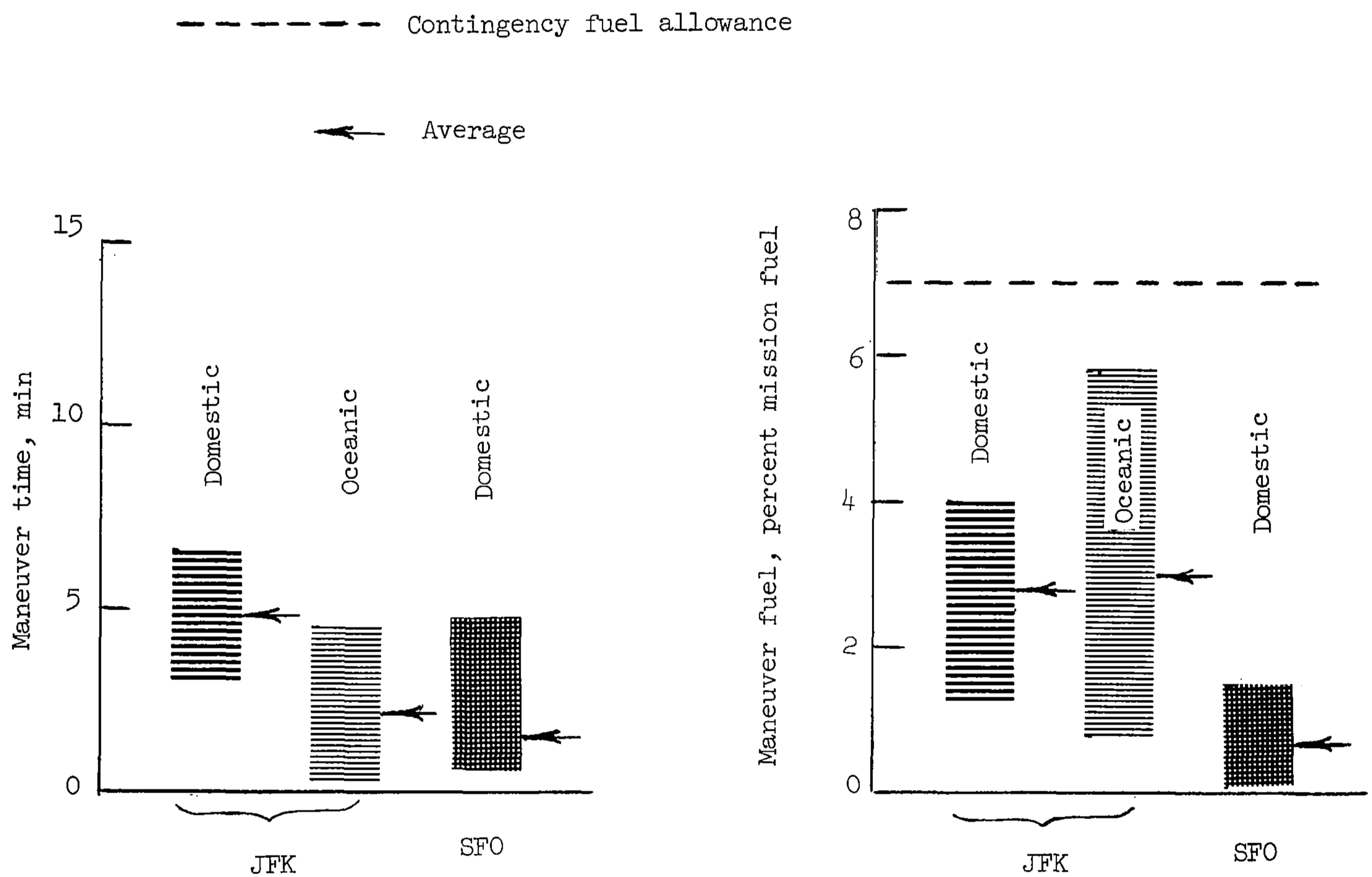
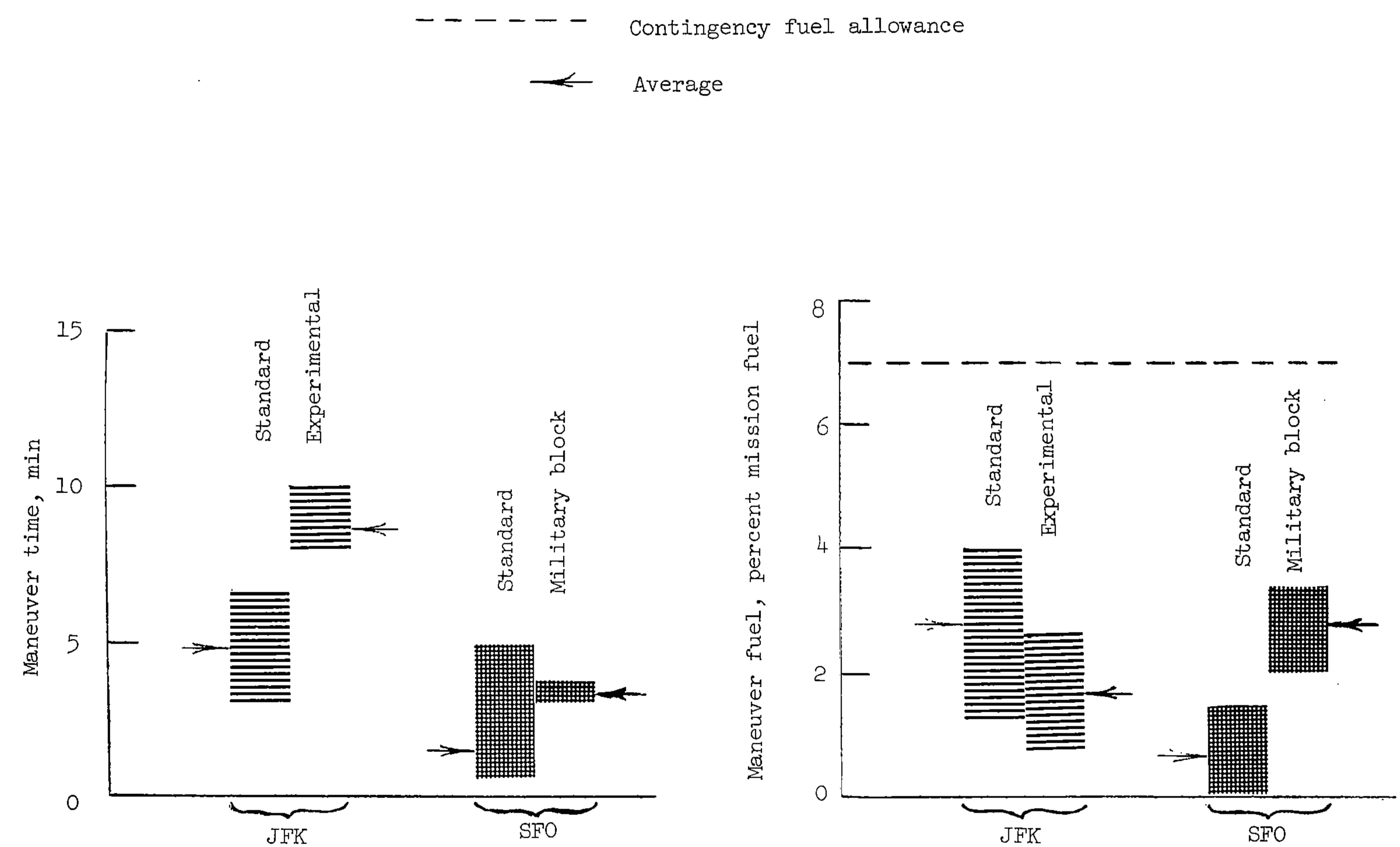


Figure 26.- Communication and navigation workload in arrivals.



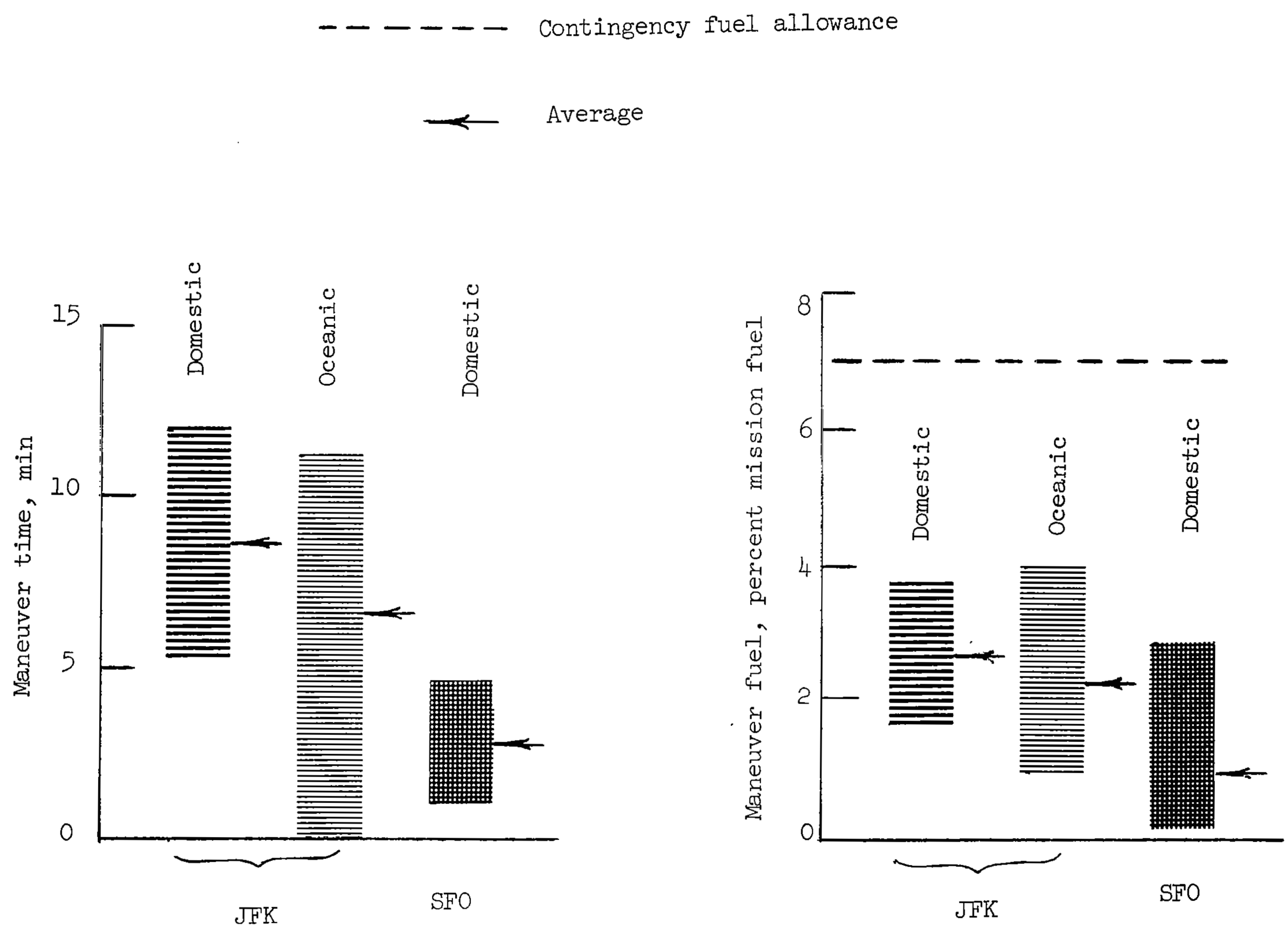
(a) Standard departures.

Figure 27.- Maneuver time and fuel for departure and arrival operations at JFK and SFO.



(b) Comparison of standard and special domestic departures.

Figure 27.- Continued.



(c) Arrivals.

Figure 27.- Concluded.

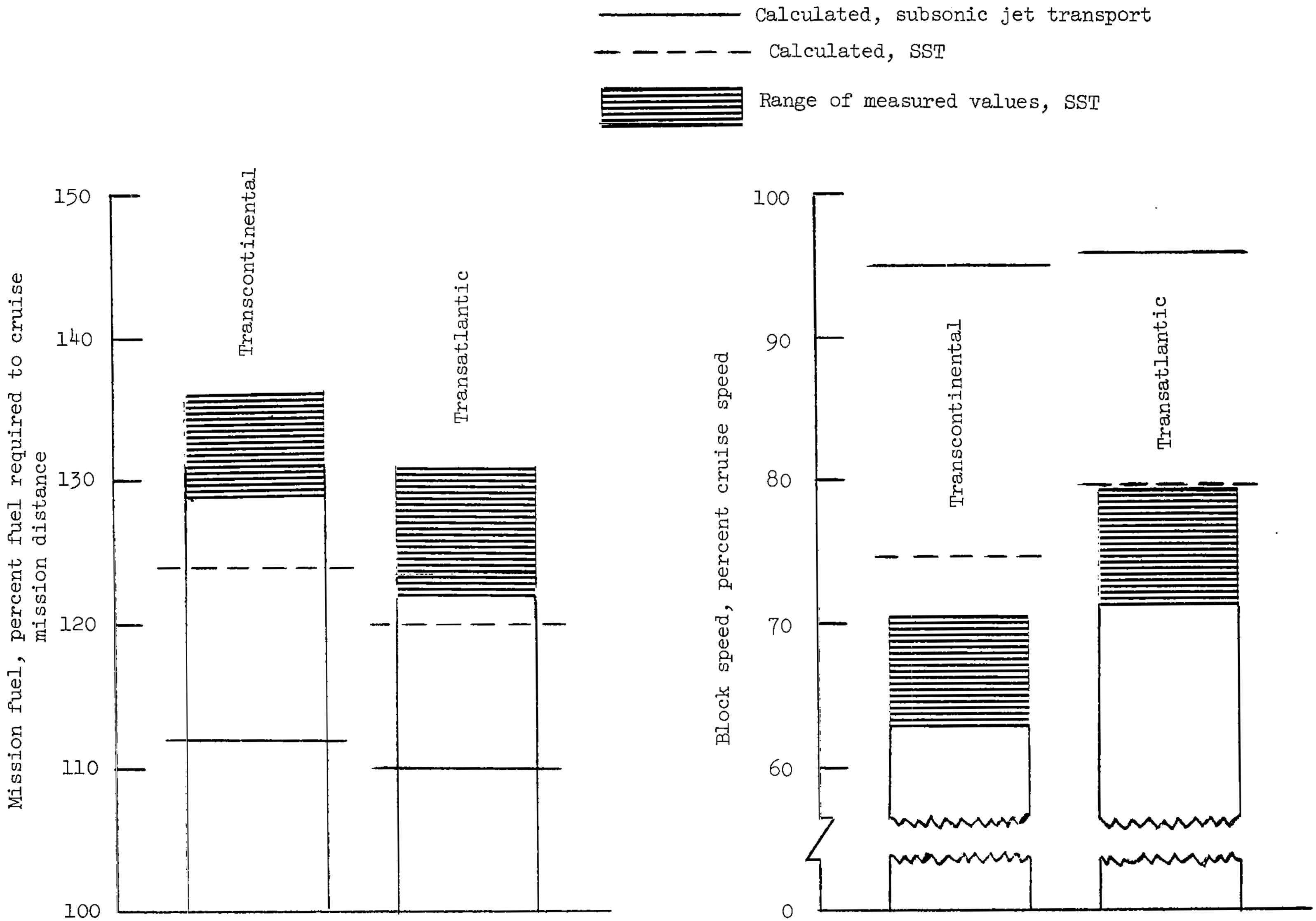


Figure 28.- Comparison of mission fuel and block speed for SST and subsonic jet transport.

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